# Reliable communication stack for flexible probe vehicle data collection in vehicular ad hoc networks

Paulin, Thomas

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# RELIABLE COMMUNICATION STACK FOR FLEXIBLE PROBE VEHICLE DATA COLLECTION IN VEHICULAR AD HOC NETWORKS

By Thomas Paulin

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|---|---|
| PhD Supervisors: | Associate Professor Tatiana K. Madsen<br>Aalborg University, Denmark |
| | Professor Dr. Hans-Peter Schwefel<br>Aalborg University, Denmark<br>Forschungszentrum Telekommunikation Wien, Austria |
| | Dr. Sandford Bessler<br>University of Technology Vienna, Austria<br>Forschungszentrum Telekommunikation Wien, Austria |
| PhD Committee: | Professor Dr. Sonia Heemstra de Groot,<br>Technical University Eindhoven, The Netherlands |
| | Professor Alexey Vinel,<br>Halmstad University, Sweden |
| Chair: | Associate Professor Henrik Schiøler<br>Aalborg University, Denmark |

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aauf@forlag.aau.dk
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| Ph.D. Student: | Thomas Paulin |
| Supervisors: | Associate Professor Tatiana K. Madsen, Aalborg University<br>Professor Dr. Hans-Peter Schwefel, Aalborg University<br>Dr. Sandford Bessler, University of Technology Vienna, Austria |

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This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

# English Abstract

Traffic congestions caused by high vehicular densities are an ever increasing problem for both personal and professional transportation, resulting in significant losses each year. While expanding the road infrastructure often offers a short term solution, more intelligent approaches are necessary to equally distribute the traffic demand throughout the available infrastructure. To enable intelligent road infrastructure traffic management, detailed knowledge about both current and the historical states are necessary. Equipping vehicles with processing and communication devices enables them to sense their own state and that of their environment through existing built-in sensors as they travel through the road infrastructure. This makes the vehicles ideal candidates for generating both traffic information that is relevant for other drivers as well as any other type of information generated by sensors carried by vehicles given a possibility to support applications that go beyond traffic monitoring.

A key challenge in the collection of probe vehicle data, i.e., sensor data generated by vehicles, is to balance the resources used for data collection and benefits from data usage. Given variable application requirements, large amounts of vehicles and their increasing number of sensors, it is infeasible to collect all sensor information everywhere and at all times due to resource constraints. Rather, the amount of generated and collected sensor data should be limited to only what is strictly necessary, by applying efficient data collection strategies.

The purpose of this work is to analyze and improve the probe vehicle data collection from a management and communication point of view, in the context of an 802.11p based, challenged communications infrastructure. We analyze the possibilities of using a distributed set of access points, so called road-side units, to facilitate the collection of probe vehicle data from the vehicles and propose methodologies that mitigate the associated challenges. Specifically, we define how management of probe vehicle data can be realized in such an environment, allowing application to specify when and what sensor data they need. From the communication point of view the main thesis contributions are three-fold; 1) We define and evaluate an approach that enables the distribution of a communication session over multiple road-side units when the communication requirements exceed the communication resource a single access point can provide for delay tolerant applications. 2) We improve the information exchange between road-side units and vehicles by identifying communication characteristics of the road-side unit and use them to determine the optimal location at which the information exchange should occur. 3) We extend the coverage range of the road-side units through vehicle to vehicle communication by modifying an existing routing algorithm, improving both delivery rate and communication overhead.

Applying the proposed methodologies on the collection of probe data provides applications with a set of tools that can be used to realize their requirements. Management of what data is collected frees up resource for a wider range of applications as unnecessary data collection can be switch off when not needed, while at the same time making it possible to increase resolution if needed. Using other vehicles as forwarders can reduce the collection delay from minutes to seconds, if the network

topology allows it, and scheduling the communication at the optimal distance to the road-side unit reduces communication overhead and distributes the resource consumption over time.

# Danish Abstract


Forstyrrelser og forsinkelser i trafikken pga. kødannelse er et stadigt stigende problem med hensyn til både personlig og erhvervsmæssig transport, og medfører betydelige tab hvert år. Udvidelser af infrastrukturen tilbyder ofte kun en midlertidig løsning, hvorfor mere intelligente løsninger, som er i stand til at distribuere trafikken ud over vejnettet, er nødvendige. For at gøre det muligt at indføre intelligent administration af trafik, er detaljeret viden om både den nuværende og historiske trafiksituation nødvendig. Ved at udstyre køretøjer med databehandlings og kommunikationsudstyr, er det muligt at gøre dem i stand til at opsamle data om deres egen tilstand såvel som tilstanden af deres omgivelser. Dermed er køretøjer ideelle kandidater som kilde for dataopsamling af både trafikinformation, som er relevant for andre bilister, såvel som indsamling af data som går udover indsamling af trafikdata.

En central udfordring, mht. sensor data indsamling fra køretøjer, er at kunne opnå ligevægt mellem hvad der bliver indsamlet, de tilgængelige ressourcer og applikationernes krav. Kombinationen af variable applikations krav, antallet af køretøjer, og deres stigende antal sensorer, gør det urealistisk at indsamle alt data, overalt og altid. I stedet, er det nødvendigt at håndtere data således kun data der er nødvendig ifht. applikationernes krav indsamles ydermere er det nødvendigt at indsamle data så effektivt som muligt.

Formålet med dette arbejde er at analysere og forbedre dataindsamling af sensor data fra biler m.h.t. administration og kommunikation, i forbindelse med en 802.11p baseret kommunikationsinfrastruktur. Vi analyserer data indsamlingen af sensordata når man bruger et sæt af distribuerede adgangspunkter, også kaldet road-side enheder, baseret på denne analyse foreslår vi løsninger som kan overkomme disse forhindringer. Derudover definere vi tre kommunikations metoder som forbedrer kommunikationen i ovenstående system: 1) Vi definerer og evaluerer en kommunikationsprotokol som gør det muligt at distribuere en kommunikations session over flere road-side enheder, når behovet for kommunikationsressourcer overstiger hvad en enkelt road-side enhed kan tilbyde. 2) Vi forbedrer udvekslingen af information mellem road-side enheder og køretøjer ved at karakterisere kommunikationsprofilen af den enkelte road-side enhed i et såkaldt performance map, som kortlægger en ydelse med en specifik geografisk placering således at den optimale placering kan identificeres. 3) Vi forbedrer dækningen af en road-side enhed gennem køretøj til køretøj kommunikation, ved at modificere en eksisterende algoritme, hvorved både pålidelighed og ressourceforbrug optimeres.

Ved at anvende de foreslåede metoder til indsamling af sensor data kan vi udstyre applikationer med en række værktøjer som gør dem i stand til at indsamle præcis den information som de har brug. Ved at administrere præcist hvad der bliver indsamlet kan vi frigøre ressourcer til andre applikationer samtidigt med at vi tillader mere detaljeret sampling hvis nødvendigt. Ved at bruge andre køretøjer til at forwarde data, kan vi reducere tiden fra sensor data er produceret fra minutter til sekunder, hvis topologien tillader det. Optimering ved hjælp af schedulering af kommunikation når bilen er i en gunstig position til at kommunikere med road-side enheden kan både reducere overhead og

distributed ressource forbruget over tid.

# Contents

# List of Figures

# List of Tables

# Chapter 1

## Introduction

Intelligent Transportation Systems (ITSs) cover a large family of data driven applications that target to improve transportation related use-cases and scenarios. Spanning across all transportation means and platforms, both localized and end-to-end aspects of personal and freight transportation can be monitored and the collected information can be used to provide customized optimizations for general and individual needs. Main application areas consists of:

- Logistics – Improving predictability through detailed tracking and planning of how goods are progressing along their intended route.
- Inter-modality – Solving transportation needs across all available platforms for finding cost, time or resource efficient solutions.
- Management – The identification and optimization of large scale transportation systems to identify bottlenecks and means to avoid them.
- Safety – Enriching drivers with exact and detailed information about potential upcoming hazards, with the purpose of significantly reducing accidents.

Example applications range from providing passengers with up-to-date information on when the next public transport will arrive over large scale management applications that identify bottlenecks and dynamically find alternative routes or transportation means to overcome them to automatic itinerary rebooking on missed connections due to delay. While the non-functional requirements vary from application to application, all ITS use-cases have one main functional requirement in common; having access to the relevant information, thus making reliable and timely collection, processing and dissemination of information is a key pillar in all variants of ITSs, which allow the participants, drivers, traffic managers and logistics personnel, to make well-informed decisions.

Safety applications are the primary drivers pushing for vehicular ITS and its deployment. These applications depend on vehicles equipped with processing and communication capabilities that enable frequent status updates to be exchanged between vehicles and provide drivers with early warnings w.r.t. potential hazards; upcoming congestion, emergency breaking vehicle ahead, etc. Vehicles equipped with these capabilities, traveling through the largest man build infrastructure, the road infrastructure, makes them the perfect candidates for collecting status information about the road infrastructure and its surroundings. As vehicles are continuously equipped with additional, and increasingly advanced, sensors, the opportunities go beyond collecting traffic information. At the same time, the increase of data source increases resource requirements.

The motivation of this work is driven by the expectation that future applications can be realized through the collection of sensor data from a fleet of vehicles traversing the road infrastructure. Their mobility and the sensor they are equipped with makes widespread monitoring possible. However, before such applications can be deployed, we need to understand the limitations and challenges of using vehicles as a source of information.

The following sections describe the environment considered in this work and define vehicular sensor data to an extent necessary to understand the problem formulation and statement, see Section 1.1 and Section 1.2, respectively. Afterwards, we describe the methodology and the contribution of each chapter together with the thesis outline in Section 1.3.

## 1.1 Environment, Probe Vehicle Data and Background Information

In Europe and the United States of America the two predominant approaches for the realization of vehicular safety applications are ETSI ITS-G5 [7] and IEEE Wireless Access in Wireless Environments (WAVE) [8, 9, 10, 11]. Both define the applications that these systems will provide and the communication stacks and system architectures that enable them. Similarly, both intend to use IEEE 802.11p as the primary communication channel for data exchange between the participants. The two standardization efforts consider the following three components as being the main participants of their vehicular ITS:

- *The On-Board Unit*: Vehicles are anticipated to be equipped with processing and communication devices, i.e., the On-Board Unit (OBU), such that they can exchange information *directly* with the vehicles (that also are equipped with OBUs) around them and to interact with the infrastructure (see below). Inter-vehicle communication provides the driver with real-time information that is relevant for him or her, based on the exchanged status messages. Theoretically, any sensor within the vehicle can be tapped and the information disseminated; speed, heading, temperature, number of passengers, etc., resulting in applications that support early warning for collision avoidance, foreign objects on the road and so on.
- *The Infrastructure*: The infrastructure plays two roles. One is to allow vehicles to access traditional Internet based services, the other is to provide specialized services related to traffic information collection and dissemination. I.e., this role is typically represented by

a Traffic Control Center (TCC), a centralized point that can authenticate and authorize what information is disseminated to the drivers. The TCC collects input from various sources, ranging from drivers phone-in traffic events to in-road sensors. One of these inputs is anticipated to be vehicular sensor data.

- *The Road-side Unit*: Road-side Units (RSUs) function as communication access points between the vehicles and the infrastructure, providing vehicles access to services within the infrastructure. Besides, RSUs play an active role in the dissemination of traffic information by locally managing what is sent or processing received sensor data from the vehicles.

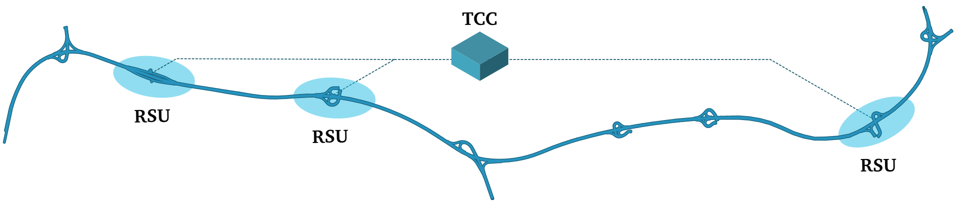


*Figure 1.1: RSUs are distributed through out the road infrastructure, enabling vehicles to opportunistically interact with service providers, here represented by the TCC.*

The road infrastructure on which the vehicles are traveling, the TCC and the RSUs are exemplified in Figure 1.1. RSUs are distributed throughout the road infrastructure, positioned at key locations where they have the largest impact w.r.t. interaction with vehicles or the largest potential for improving the traffic situation, i.e, at or before intersections, such that drivers can be informed in a timely manner and make appropriate decisions.

Communication between the TCC and vehicles is as mentioned facilitated through the RSU. The connectivity between the TCC and the RSUs is anticipated to be based on Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) over Internet Protocol (IP) while the wireless link, between RSUs and vehicles (equipped with OBUs), is done using IEEE 802.11p, described in the next section.

### 1.1.1 Communication and Message Types

IEEE 802.11p has been specifically designed for highly mobile environments and trades off bandwidth for increased robustness towards fading and multipath propagation [12]. This extends the communication range, compared to 802.11a, on which 802.11p is based on. The main mode of operation is ad hoc, which allows vehicles to communicate directly with each other, by removing the need for access points and access point association, as is typically needed in managed networks. Majority of the information that is exchanged between the nodes is designed such that it may be contained in a single messages and is transmitted using broadcast mode. Using ad hoc communication and broadcast mode allows a node to reach a larger amount of neighbors with low communication overhead and delay, when the information is relevant for multiple participants. For safety applications, and due to highly dynamic mobility, frequent status updates are used to exchange the current status between the vehicles.

The main messages exchanged between the participants are periodic status beacons, e.g., Cooperative Awareness Message (CAM), and event information, e.g., Decentralized Environment Notification Message (DENM). Periodic status beacons contain the current status of the vehicle; position, speed, heading, lane information, vehicle type, etc. This allows the vehicles to maintain a continuously updated overview of their surrounding and allows for the *detection* of potential hazards, collision due to variability in speed between two vehicles, a motorcycle in the driver's blind angle or an ambulance approaching. Event information is either identified through fusion of the continuously exchanged status information, e.g., the identification of a potential collision case, or by the vehicle it-self through built-in sensors detecting foreign objects on the road.

### 1.1.2 Definition of Probe Vehicle Data

Probe Vehicle Data (PVD)[1] is a general term used for sensor data that is generated by vehicles and can be categorized in the same way as above, as either periodic or event driven. The differences are that PVD implies that the generated data is collected centrally, is not limited to traffic related use-cases, and differs w.r.t. the applications it is used for. As an example, collection of event PVD may be used to collect information on areas with frequent emergency breaks or high noise pollution, if the vehicle has a noise sensor, while periodic PVD may be used to identify the reason of emergency breaking or the actual noise values throughout those areas. In general, event PVD informs the receiver about events that have occurred while periodic PVD may serve as a monitoring tool or provide details about detected events. The core elements of PVD, independent of type, are:

- Location – Where the probe is generated.
- Time – When the is probe generate.
- Type – Which sensor is sampled or event is detected.
- Value – What is the sensor value or event details.

While the two types of PVD are similar w.r.t. their functional requirements and depend on the same methodology for collection and communication, they have, in most cases,

[1] In this work we use PVD, sensor data, probes and probe data interchangeably.

orthogonal non-functional requirements; the priority and delay requirements of a detected accident that requires external assistance are significantly higher than the collection of travel time information. To focus the thesis we limit this work to periodic PVD, mainly as this allows us to investigate general collection challenges and methodology rather than fulfilling selected requirements of a specific application.

In the context of PVD and the considered RSU infrastructure, the role of the RSUs is to facilitate the collection of PVD from vehicles as they pass by. The collected PVD may then either be pre-processed and forwarded to the TCC or processed locally, depending on the use-case and application that the PVD is used for. In this work, we use the TCC as the centralize collection point, but the majority of challenge identified apply to both approaches.

## 1.2 Problem Formulation, Statement and Research Questions

Vehicles traversing the road infrastructure while generating PVD are expected to enable a large range of applications for traffic state monitoring, sampling of the environment etc. However, given varying application requirements, w.r.t. sampling rate, sensor data type, location etc., and the number of sensors that may be sampled, is is infeasible to collect everything everywhere. We use the following, simplified equation, to initiate the discussion. The equation states the relationship between communication resources and communication requirements as a function of key parameters:

$$\frac{\text{available resources}}{\text{required resources}} = \frac{\text{number of RSUs} * \text{communication capacity per RSU}}{\text{number of OBUs} * \text{number of sensors} * \text{driving distance} * \text{sampling frequency}} \tag{1.1}$$

While the enumerator in Equation 1.1 is not constant, unnecessary increase in the number of RSUs is associated with unnecessary costs. On the other hand, the denominator can be expected to grow at a significant rate, especially if applications have high probe resolution requirements (sampling rate), more and more vehicles are being equipped with an OBU, which is a prerequisite for safety applications, and an increasing number of sensor types becomes available. This may potentially result in an unsustainable system where the demand for resources grows faster than the resources become available.

The challenges that can be expected w.r.t. collecting PVD using a geographically distributed RSU infrastructure can be visualized using a time-space diagram like the one illustrated in Figure 1.2. The figure shows a plot of synthetically generated vehicular traces, plotting the distance traveled as a function of time. The expected progress of the vehicles, is illustrated by the diagonal line, and is what can be expected if the vehicle drives at the allowed road speed. However, at around 3000 meters, an event has occurred, causing the vehicles to drive below allowed speed. Probes are generated along the trajectory of the vehicles and delivered at the RSU, identified by the black horizontal line. The horizontal bar identifies the Area of Interest (AOI) and $v1$ identifies one specific vehicle. $t1$ and $t2$ define the time where the vehicle generate a specific probe at the AOI and delivers it to the RSU, respectively. Using Figure 1.2 as reference, we can formulate the following challenges, referring both to the denominator in Equation 1.1 and the vehicle trajectory:

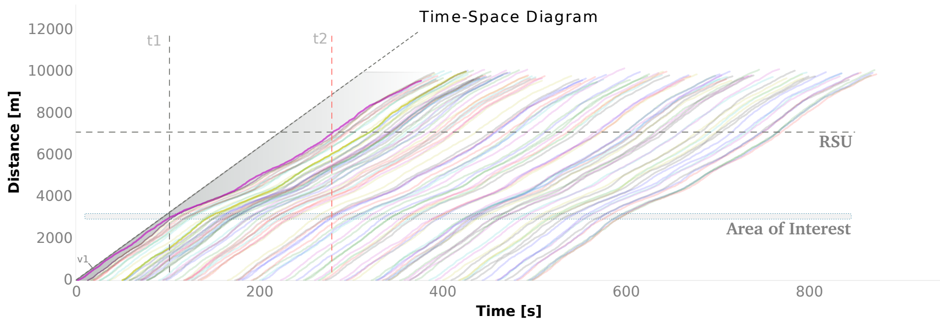


*Figure 1.2: Visualization of challenges w.r.t. PVD collection using a distribute RSU infrastructure.*

- The total number of probes generated depends on:
  - Number of OBU – The percentage of vehicles in the figure that can be expected to deliver data.
  - Sampling frequency – This corresponds to the resolution of the trajectory of each vehicle.
  - Number of sensor – When the number of sensors is increased so is the number of traces per vehicle.
  - Driving distance – The farther/longer each vehicle travels the more periodic probes can be generated. This impacts both the total number of probes generated but also, depending on the distance between RSUs, the amount of data an individual RSU should be able to receive.
- Delay between probe generation by the vehicle and probe delivery at the RSU:
  - Distance between where the probe is generated and the RSU – Defines the minimum delay between probe generation and probe delivery. Assuming vehicles follow speed regulations, this corresponds to the diagonal line in the figure.
  - Variability of the delay due to traffic conditions – This can be seen as the difference in when the vehicle would have arrived if it was driving at the allowed speed compared to

the actual delivery $t2$. Vehicles traveling faster than the allowed speed, would deliver the probes earlier, increasing the variability.

Applications, however, have, as mentioned before, varying requirements; the sampling rate of probes and the type of sensor sampled depends on the event we wish to monitor. Similarly, depending on the use-case, the delay may or may not have an actual impact on the performance of the application. Therefore, the problem is that in order to be able to support a large range of applications, we need to be able to manage what sensor data is being collected, as otherwise, there are not enough resources to support the collection.

To be able to realize efficient PVD collection, we need to answer the following questions:

1. How can PVD be managed such that only data that is actually needed to fulfill application requirements consume resources?
2. How can the PVD collection be optimized such that the minimal amount of resource be consumed to collect the PVD that is necessary?
3. How can collection delay due to the travel time between probes being generated until they are collected be minimized?

In other words, the two goals of this thesis are to 1) minimize resource requirements by only collecting exactly what information is needed and 2) to reduce resource consumption by optimizing collecting of the information that is needed. To achieve these goals we need to quantify the challenges.

## 1.3 Methodology, Contributions and Thesis Outline

The methodology used in this work considers a two-step approach, where the first step is a general analysis of the problem domain. This is realized in two dedicated chapters, one analyzing the properties and limitations of connection oriented, 802.11p Infrastructure-to-Vehicle (I2V) data exchange, using field trial measurements and presenting how the different layers in the communication stack behave. The second analysis focuses on the collection and processing of PVD, i.e., what impact does the RSU distribution have on the collection delay and how do parameters such as OBU penetration rate and the PVD sampling rate, i.e., how often a vehicle generates probes, impact the accuracy of the information extracted from the collected probes. The results from both these analyses are then used as a driver for the remaining chapters that improve the overall PVD generation and collection. Specifically, in response to the above defined problem formulation we approach the following topics:

- Chapter 2 – We define a protocol that allows vehicles to distribute their communication load over multiple RSUs, when the communication requirements exceed the communication capabilities of an individual RSU. This protocol is evaluated through an 802.11p field trial, providing insights in how the different communication stack layers react in a mobile, 802.11p environment.
- Chapter 3 – We evaluate, using simulation, a large scale PVD collection scenario using realistic vehicular mobility and road infrastructure and analyze the challenges w.r.t. PVD collection in the context of a distributed RSU infrastructure. Having identified that a significant limitation for processing PVD is the variable travel time between RSU, we evaluate how this impacts three aggregation algorithms, for speed estimation.
- Chapter 4 – We define a methodology for management of PVD, named Controlled Probing, which enables applications to define exactly what, where, when and how to collect probe data. The focus is on how this type of framework can be realized in an 802.11p based infrastructure.
- Chapter 5 – We investigate how a) performance maps, that is the quantification of communication performance at specific geographic locations, can be generated and represent the communication profile of individual RSUs and b) how these performance maps can be used to improve the information exchange between RSUs and vehicles.
- Chapter 6 – We define a reliable, low overhead geographical routing communication protocol that extends the communication range of RSUs and enables a) the RSUs to disseminate information to vehicles that are outside of their communication range and b) allow vehicles to forward collected PVD directly to the RSU, thus reducing the delay for important information.

The content of each chapter is mapped to the layers of the Open Systems Interconnection (OSI) model in Figure 1.3.

## 1.4 Mapping between Project and Thesis Content

This thesis is based on research highlights from a series of COMET projects on the development and reliability of ITS; ROADSAFE, ITS Evolution and Future ITS. Each of the three projects had a main focus; ROADSAFE investigated the potential of two way communication between a OBU and a RSU, resulting in the field trial measurements presented in Chapter 2. ITS Evolution focus area was on the development of the management of PVD data to reduce the resources necessary to realize their collection, see Chapter 3 and Chapter 4. Future ITS used the lessons learned and generated the notion for performance maps, Chapter 5 and GeoNetworking, Chapter 6.

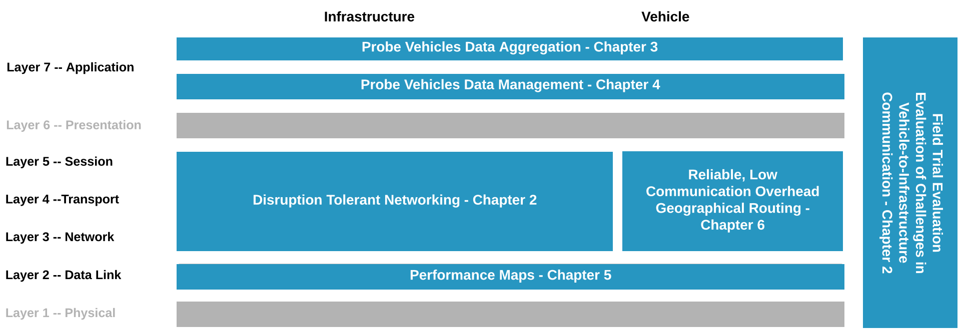


*Figure 1.3: The main topics investigated in this work mapped to the corresponding layers of the OSI model.*

# Chapter 2

# *Use-case Study of 802.11p-based Infrastructure-to-Vehicle Communication*

The work in this chapter is based on the system architecture described in Section "Environment, Probe Vehicle Data and Background Information", and analyses the communication challenges from an Infrastructure-to-Vehicle (I2V) interaction point of view. The goal is to understand how the different layers of the communication stack react to a communication scenario dominated by high mobility and frequent topology changes. As a secondary objective, we investigate how a communication session can be realized using multiple Road-side Units (RSUs), when the communication resource requirements surpass the resources a single RSU is capable to provide.

The content of this chapter is based on the Disruption Tolerant Networking (DTN) protocol defined in [5] and the field trial measurements published in [4]. The DTN simulation of [5] has been extended with additional DTN mechanisms and results while the problem statement and usage of the field trial measurements have been extended to a general analysis of I2V communication.

## 2.1 Introduction

Vehicle drivers and passengers are used to and expect continuous access to Internet based services such as real-time traffic information, audio/video streaming, email access, browsing etc. This is currently possible, primarily due to heavy deployment of cellular base stations, especially in urban and densely populated areas, providing access to those services. Such services can't necessarily be expected from an IEEE 802.11p based infrastructure of access points (RSUs); their deployment is anticipated to be sparse, only covering key points of the road infrastructure. In combination with high mobility of vehicles and a relatively shorter communication range than cellular, a vehicle can only expect short, intermediate intervals during which it is able to exchange information with the infrastructure. These limitations impact what services, especially if data heavy, can be provided.

Due to the dominance of limited, short-term communication opportunities in I2V, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V), the primary modes of 802.11p operation is ad hoc based. Applications and services are designed such that the information they depend on can be exchanged using individual transmission events. For V2V safety applications this is perfectly suitable; collision probability of two vehicles can be estimated by having the information about each vehicle's current position, speed and heading. Similarly, combining the exact position of the vehicle with the information that it is currently executing an emergency breaking maneuverer is enough to notify the vehicle heading towards this location that there is a hazardous event ahead. These design choices make it challenging to provide non-safety services that depend on stream based communication, i.e., payloads that span over multiple Media Access Control (MAC) layer frames.

Non-safety applications that are expected to be provided through the RSU infrastructure, and that depend on reliable, stream based communication consist of traffic management and information services. Road operators' traffic management systems can be improved by collecting traffic information from vehicles about the current traffic situation, and disseminating the collected information to geographical locations where it is relevant. V2I and I2V communication can be used to enable the exchange of non-safety related traffic information like the collection of Probe Vehicle Data (PVD) from On-Board Units (OBUs) for global traffic state detection and the dissemination of traffic information by RSUs or even to provide additional services to the vehicles, e.g., imagery from the upcoming events.

A specific branch of applications that are independent of the timeliness of or delays in the communication are said to be delay tolerant. For example the collection of probe data for long term monitoring of trends in pollution levels is significantly more delay tolerant than the collection of probe data for continuous traffic monitoring. The term DTN, when used in communications networks, has primarily two different, but not necessarily mutually exclusive, definitions; *Delay* Tolerant Networking and *Disruption* Tolerant Networking. While the first definition has its origin from space based communication[13], where the communication sufferers from high delays due to the distance the signal has to travel, the second definition is more suitable for the Intelligent Transportation System (ITS) environment, as the application must be capable to handle disruptions due to the distance the vehicle has to travel between communication opportunities. For disruption tolerant applications, i.e., without strict delay requirements, a session can therefore be extended for as long as necessary, until it is finished, without impacting the performance of the application.

## 2.2 Problem Formulation, Statement and Contributions

This section discuses the problems in V2I communication and define the exact problem statement that are approached and the exact contributions of this chapter. There are followed by a presentation of the main terminology used in this chapter and the outline of the remaining sections that investigate the identified problems.

### 2.2.1 Problem Formulation

The main problem in stream based V2I and I2V communication is caused by the limited contact duration between the RSU and the vehicle, resulting from a combination of high mobility and limited radio coverage. This fathers two sub-problems, namely how to utilize the available connectivity and what to do when the amount of data that has to be communicated is larger than a single connectivity duration allows. To achieve a high utilization of available resources during a single passing of RSU, we need to understand how the individual layers of the communication stack react to the frequently changing communication environment and its properties. Distribution of a communication session over multiple RSU requires a method for detecting that a communication opportunity is over and that can enable the continuation of an interrupted session at a later point in time.

W.r.t. utilization of communication opportunities, the first problem is to be able to correctly identify when to communicate such that the opportunity can be utilized optimally. This includes the vehicles being able to detect the presence of the RSU; when it arrives within the communication range of the RSU but also when it leaves it. Typical highway speeds of 100 kilometers per hour and a, theoretical, communication range of up to 1000 meters means that contact durations during which the OBU and RSU can exchange data are measured in tens of seconds rather than minutes. During this time, the vehicles have to initiate, execute and, preferably, finalize the exchange of the data. Thus, the vehicles have to be able to detect when the communication can be initiated, while balancing utilization and taking the quality of the channel into consideration. Due to signal decay in wireless communication over distance, attempting to communicate under poor communication conditions can result in low success probability in these areas. In these areas, the vehicle's communication attempts are more probable to create interference for other vehicles that have more favorable, for example nearer to the RSU, conditions. Postponing the communication too much reduces the availability in the time dimension, reducing the utilization of the available resources. The same characteristics apply when the vehicle is moving *out* of the coverage range of the RSU.

Compared to cellular networks, vertical handover, i.e., the moving of the association of the cellular device from one base station to another, targets to find a *better* base station to continue the sessions. In 802.11p there are, at least not initially, no RSUs that can be used to handover to[1]. Instead, the session needs to be halted until another communication opportunity is available, i.e., the next RSU. This requires mechanisms that can identify the

[1]Horizontal handover from 802.11p to cellular could enable the continuation of the session if the OBU is equipped with an alternative communication device.

interruption and handle the communication session in such a way that it can be continued at a later point in time without data loss.

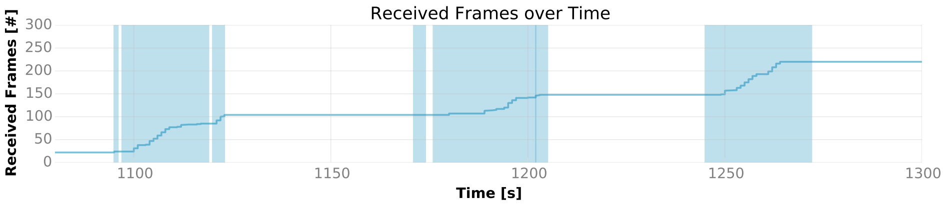


*Figure 2.1: The perception of being within communication range of a RSU and the received frames as seen from the point of view of a OBU driving through an area with three RSUs*

We use Figure 2.1 as a motivation and illustration of the challenges that can be expected in the connectivity and communication flow between the OBU and the RSU. The figure shows a trace of received messages recorded by an OBU while it is passing three RSUs. The shaded parts represent the point in time where the vehicle was aware of the RSU. This is triggered by the OBU receiving a beacon from the RSU and end when more than 10 consecutive beacons are missing. The plot shows how the accumulated number of received frames increases over time. It can be seen that even though the OBU passed exactly three RSUs, six blocks are depicted. This is due to the vehicle receiving a single message from the RSU while it is at the very edge of the RSU's communication range, believing that it can communicate with the RSU. Secondly, the accumulated frame reception plot does not increase as a function of time as could be expected, but has variations in the incline, even when the OBU is within the communication range of the RSU. The latter is caused by the high communication loss while technically within the communication range of the RSU.

Specifically, in this chapter we investigate how the MAC, networking and application layers are impacted by I2V communication in a highly mobile motorway scenario. Identifying the main limiting factors in I2V communication and how do they impact the performance we answer what needs to be taken into account when performing I2V communication.

### 2.2.2 Contributions

The main contribution of this chapter consists of the execution and quantification of a field trial evaluation of how the communication environment is experienced by the application layer, using a DTN implementation. Based on the findings, the communication is improved by introducing mechanisms that cope with the identified challenges. The contribution consists of the following topics:

- We define a communication protocol that enables reliable communication in the V2I setting and provides DTN functionality that distributes the communication over multiple RSUs. The functionality is achieved through:
  - In-node caching of undelivered data, in both upstream and downstream communication. I.e., V2I and I2V.
  - Cross-layer optimization using MAC layer acknowledgments on application layer.
- We evaluate the above communication protocol using an 802.11p field trial, and gain insights into both how the application layer experiences the communication while using lower layer measurement to explain what causes the performance limitations. In particular we discuss the following metrics:
  - The End-to-End (E2E) communication delay for various payload sizes and how this delay is distributed between active communication and waiting for communication opportunities as well as the achieved application layer good-put.
  - Number of interruptions and the duration of uninterrupted communication sessions as expressed by the number of consecutively successfully delivered MAC layer frames and the impact of MAC layer retransmissions.
  - Various implementation specific metrics used to explain the performance – I.e, architecture specific limitations, caching of data when communication is interrupted etc.
- Definition and evaluation of two mechanisms that can cope with the identified challenges using trace based simulation:
  - Improved in-node caching that ease the assumptions on when to initiate caching of data w.r.t. the vehicle being out of coverage.
  - A modified MAC layer retransmission approach that distributes retransmissions with respect to the channel rather than avoiding congestion.

### 2.2.3 Terminology

- Interruption – A long or short term loss of connectivity between the OBU and the OBU.
- Inter-RSU – Events occurring *between* two RSU. For example an interruption caused by the OBU leaving the communication range of a RSU, usually resulting in a *long* interruption.
- Infra-RSU – Events occurring *within* the communication range of an individual RSU. For example communication loss due to interference or loss of line of sight between the RSU and the OBU, usually resulting in a *short* interruption.
- RSU pass/passing – A vehicle traversing the full communication range of a RSU.

### 2.2.4 Outline

The remaining of this chapter is organized as follows. Section 2.4 describes 802.11p and Wireless Access in Wireless Environments (WAVE) to cover the environment and system architecture relevant for this chapter. Section 2.3 presents and discusses the related work with regards to wireless communication and DTN in general. This is followed by the design of the DTN solution used to enable communication that copes with inter-RSU interruptions in Section 2.5. Section 2.6 and 2.7 describe the configuration of the field trails and the corresponding results, respectively. Main lessons learned are summarised at the end of Section 2.7.4 and build upon, to improve the DTN solution, in Section 2.8. Finally, we present the conclusion and future work in Section 2.9 and 2.10, respectively.

## 2.3 Related Work

The related work section is split up in two parts. The first discusses general RSU communication range quantification and the second part investigates related work on the topic of DTN.

### 2.3.1 Vehicle-to-Infrastructure Communication

Majority of 802.11p based measurements focus on physical layer performance in a large variety of hardware configurations and mobility scenarios. As the main focus of 802.11p based applications excursively depend on individual, self-contained message transmissions, this prioritization is highly relevant, but, the measurements don't reflect over session based communication. Rather, we target to evaluate how large application layer payload behave using this system.

Some of the first published 802.11p application layer results were presented in [14]. Based on single-hop broadcast communication at predefined, static distances between the 802.11p radios, it was shown that the performance suffers from large payloads as well as distance. While these results provide insight into the size-distance relation, they can be overly optimistic as they do not take into account how packet loss impacts session based communication. Also the measurements were done using only one channel. In our approach we introduces mobility, channel switching and session based communication.

For additional V2I topics, please refer to Section 5.1.3.

### 2.3.2 Disruption Tolerant Networking

In [15] the authors define that a system can handle failure, due to either node failure or communication link failure, in three ways. Restart, resume (possibly using check points) or to give up and conclude that an restart approach can lead to an unstable execution of tasks. In our work, we assume that circumstance exist under which restarting a communication task, is in most cases infeasible, due to too limited resource while giving up on a task requires more insight into the properties of they system that we evaluate, before it should be considered.

There are several approaches used to cope with disruptions in a communication network, depending on the type of interruptions and the type of communication channel utilized. If the Round Trip Time (RTT) delay is very long then the bundling approach is used [13]. Another approach has been used by [16] and later on in the CHIANTI project [17]. This approach is based on known, or advertised, proxies and client applications which mimic the behavior of stable TCP connections between the proxy and the service itself, leaving the original client and service untouched. In CHIANTI the proxy can be placed anywhere within the infrastructure as long as the CHIANTI client knows the IP address of it as all communication between CHIANTI client and CHIANTI proxy is through either TCP/IP or UDP/IP and utilizes off the shelf wireless components. The system has been tested in trains where the GSM/GPRS connectivity varies, for web browsing, streaming and email exchange.

The work in [13] proposes three different solutions. One is similar to CHIANTI, where they utilize a proxy and a middleware on the client, the second consists of only a client side middleware and the third suggests modifying the service provider application as well as having a client side middleware. By having a client side middleware it is possible to manipulate the client application to think it is still connected, yet there is no control on the service provider side. The third solution removes the need for routing the traffic through the proxy, but extensive work to modify existing services in order to support DTN is required.

When dealing with disruptions as well as delay prone connections [18] proposes to combine DTN with bundling to receive large amount of data from space satellites. The bundles are delivered at multiple ground stations and then routed to a commonly known node where all the data is reassembled. While the same principle should be applied in the RSU context, more insight is needed about the resources an individual RSU can provide, such that the bundle size can be optimized.

## 2.4 Vehicle-to-Infrastructure Communication in Standardization

Currently, two IEEE 802.11p based standards for vehicular safety applications exists: IEEE WAVE and ETSI ITS-G5. The work in this chapter is based on the functionality provided by WAVE, but both stacks are mentioned in order to discuss the general applicability of the results. Figure 2.2 show the communication stacks provided by the two standards.

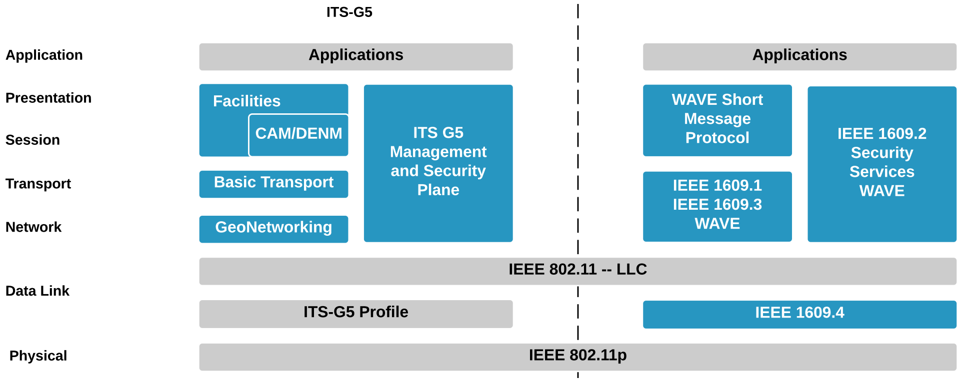


*Figure 2.2: The WAVE stack, illustrating the different layers in WAVE and parallel components which work orthogonally to the vertical layers. Figure based on figure from [9].*

IEEE 802.11p is a specific configuration derived from the 802.11 standard that modifies two aspects; it defines the main mode of operation to be ad hoc based, thus removing the need for access point association and improves robustness towards fast mobility and longer communication ranges. Both modifications stem from the characteristics of the vehicular environment, where highly mobile devices have to communicate reliably and with low delay. In the context of non-safety communication, the lack of access point association means that other mechanisms are necessary to enable session based communication.

In WAVE single-channel and multi-channel, based on periodic channel switching, operational modes are introduced. Figure 2.3 shows the two modes in which WAVE operates. In multi-channel operation the radio switches between the two channels at a 50 millisecond interval. For non-safety data communication, similar to what is evaluated in this chapter, only communication in the Service Channel (SCH) is allowed, while the Control Channel (CCH) is restricted to safety communication and service announcements: In WAVE discovery of services provided by other nodes, e.g., by the RSU, has been done by introducing a service announcement message, named WAVE Service Announcement (WSA). This message contains information about what services are provided and on which channel, i.e., which SCH. On reception of a WSA message, the OBU can decide whether to use the provided service, by switching to the specified SCH.

While WAVE does envision an Internet Protocol (IP) based communication stack, it is not available as of time of writing. Rather, it introduces the WAVE Short Message Protocol (WSMP). The WSMP stack provides the WAVE Short Message (WSM) messages, a User Datagram Protocol (UDP) like message format, which allows significantly more fine-grained control of the communication by the upper layers, i.e., per packet power level, on

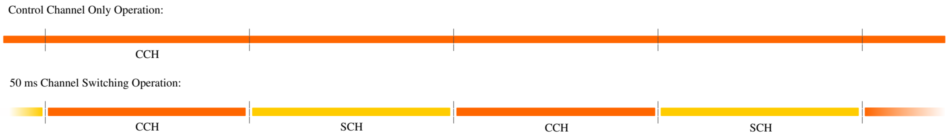


*Figure 2.3: Continuous CCH operation versus channel switching between CCH and the SCH*

which channel to transmit the message, the number of retransmissions when using unicast, etc. It also uses MAC based addressing rather than IP.

The overall concept of ETSI ITS-G5 is similar to WAVE, as both define the safety applications and communication stack enabling them. From a V2I perspective, two differences are relevant; ITS-G5 does not provide a service announcement, but has a dedicated field in the safety message that allows to specify that the sender is a RSU. This allows an OBU to detect the RSU, but does not contain the information of what services are provided.[2] Secondly, even though multi-channel operation, either through channel switching as in WAVE or through multiple radios, is envisioned, it is not as integrated into the concept as in WAVE. This means that in ITS-G5, safety and non-safety communication have to share the communication resources.

## 2.5 Concept Design for Disruption Tolerant Networking

This section describes a system architecture and protocol design that enables the realization of DTN in a distributed network of RSUs. These two components in combination enable vehicles to reliably exchange information, either up or download, with services within the infrastructure, by opportunistically utilizing RSU as they become available. Key functionalities provided consists of:

- Seamless, vertical handover between RSUs through in-node caching.
- Detection and utilization of communication opportunities.
- Proxy based data retrieval and upload.

The design is driven by the expectation that initially, neither WAVE nor ITS-G5 will have a full Transmission Control Protocol (TCP)/IP stack implementation available. Even so, I2V and V2I communication will be dependent on mechanism that are capable to provide disruption tolerant networking in the context of an RSU infrastructure. Default version of

[2]At the time of writing the RSU specific components of a safety messages in ITS-G5 is left undefined, so functionality similar to WAVE is possible and can be expected.

TCP do not cope well with unpredictable interruptions and, the disruptive nature of the communication makes it challenging for an application to maintain a connection with a service in the infrastructure, risking it to time-out.

### 2.5.1 Overview and Concept

The proposed DTN solution consists of three components; a middle-ware, running on the OBU and RSU, managing the communication aspects and an application layer Service Access Point (SAP), responsible for interacting with external services. This architecture is illustrated in Figure 2.4.

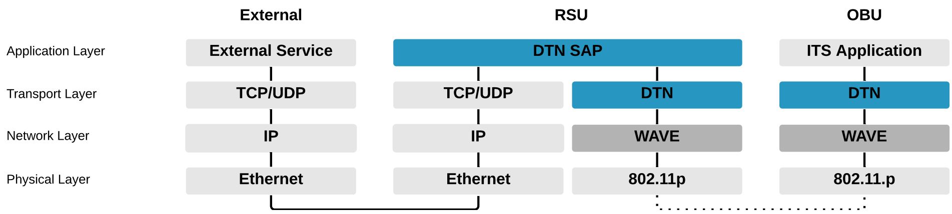


*Figure 2.4: Components of DTN. The middle-ware, represented by the two DTN boxed and the service component.*

The three components provide the following functionality:

- The middle-ware on the OBU allows application to request payload or upload payload to a given service within the infrastructure. It maintains the status of each on-going session and monitors the current connectivity status, i.e., if the OBU can communicate with a RSU such that information exchange can be executed.
- The middle-ware on the RSU serves mainly as a bridge between the wireless and wired domain, enabling the data exchange between the OBU and the SAP and by processing inquiries from the OBU. It is also responsible of informing the vehicle about available SAP, as defined below.
- The DTN SAP full-fills two roles. It acts as a proxy for the application on the OBU, by interacting (requesting or uploading payloads) with the service that the application has specified and as an well-known anchor point; each DTN session is associated with exactly one SAP where upstream data is aggregated and downstream data can be access. The SAP can either be a local entity, located on each RSU, or a centralize process, located somewhere in the infrastructure.

### 2.5.2 Module Functionality

Here we describe how the communication is realized and detail the three modules further.

### Communication

The wireless communication between the OBU and the RSU, is based on a cross-layer approach, where MAC layer acknowledgements are propagated up to and used by the networking layer to determine if a message has been delivered. This avoids networking layer acknowledgements, thus reducing communication overhead, and is possible as there is no end-to-end connectivity between the OBU and the service. When using DTN with WAVE, the networking layer is implemented by the DTN middle-ware. Whenever a positive MAC layer acknowledgement is received, the next packet is sent, if any are available. If no acknowledgement is receive, the communication is interrupted and it is assumed that the OBU and RSU are out of communication range. This triggers a temporary pause in the on-going communication sessions, further detailed later on, depending on the whether the communication flow is directed from the OBU to the RSU or the other way around.

Presence of the RSU is detected by the OBU receiving beacons from the RSU, i.e., WSA messages. The amount and frequency of received beacons is a configurable parameter that, when fulfilled, triggers the channel switch between the CCH and the SCH.

### On-Board Unit Middle-Ware Functionality

On the OBU the middle-ware has to maintain status of the different sessions that are currently active and monitor the connectivity status, ready to react if the status changes. The work flow consists of receiving a request or a payload from the application on the OBU, that is targeted towards an application in the infrastructure. Independent on whether the application provides a request or payload, the data has to be tagged with the destination service, IP or host name, port, application layer protocol, ect. Using a, for the middle-ware, well-know SAP, the middle-ware uploads any content it has received from the application, addressed to the SAP when an RSU is encountered. Is a interruption during the sending of the information occurs, the middle-ware store the remaining data until a new opportunity arises, i.e., the next RSU is encountered.

During reception of a requested payload the middle-ware accumulated the data, until it is fully received and can be reassembled and provided to the application. If the communication is interrupted, i.e., the OBU stops receiving data before the all fragments of the data have been received, the middle-ware has to resume the communication session when the RSU is available.

Generally, all events are triggered by the DTN middle-ware on the OBU as 1) it already knows which sessions are on-going and need to be finalize 2) can trigger the continuation of these when in-coverage of a RSU, by recognizing that a communication opportunity is available.

### Road-side Unit Middle-ware Functionality

The middle-ware on the RSU is generally stateless. All data messages, requests and payloads, are forwarded to the, by the OBU, specified SAP. Only in the case of a query, the middle-ware has to do something actively. In such cases, it has to retrieved the specified remaining payload from the specified SAP and forward the remaining fragments to the OBU. If a interruption occurs, the remaining un-acknowledged fragments are written back to the SAP, such that the OBU can request it at a later point. In addition, the RSU continuously broadcasts information about the SAP that it is associated with, in order for the vehicle to know which one to use.

### Service Access Point Functionality

The DTN SAP is the core of the DTN approach. It provides both the temporary in-node storage, where data destined for the OBU is stored while the OBU is out of coverage, and as a secondary function it processes and executes the requests on behalf of the OBU; i.e., when an OBU wishes to access a web-server, the OBU specifies the location and the resource that it requires, and the SAP retrieves the specified resource(s).

As part of requesting of resources for the OBU, the SAP has to fragment the payload returned from the service. This is done such that an appropriate amount of fragments can be retried, corresponding to what is realistic for the vehicle to receive while passing the RSU.

### Disruption Tolerant Networking Work Flow

Figure 2.5 illustrates the concept of DTN using a scenario where the processing of the OBU request takes a significant amount of time, such that the OBU has left the coverage range of the RSU before the processing has finished.

It is assumed, but not illustrated that the OBU middle-ware has received an request from an application on the OBU for processing. This request is forwarded by the OBU middle-ware to the RSU for processing. First by the RSU, which routes it to a SAP, then by the SAP processing it accordingly. This depends on what type of request is it, e.g., a website, an file requested on a FTP server, but when the resource is received, it is fragmented and sent back to the OBU, through the same RSU which *received* the request. Based on the MAC acknowledgements, the session ends successfully when all messages have been received.

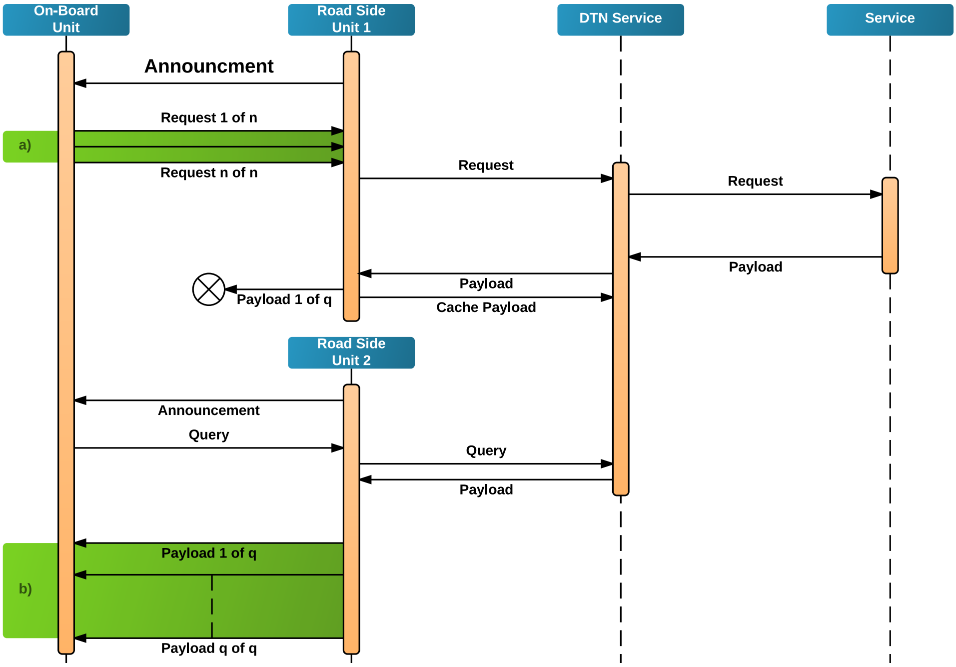


*Figure 2.5: General DTN concept. The OBU splits the payload into multiple fragments and uploads it to the RSU. When it is done, the payload is combined and in this case executed; the request is processed and the requested payload. As the processing took longer than the duration of the OBU being in coverage of the RSU, the response fails and is cached at RSU 1. At the next communication opportunity, the vehicle queries the original request which is fetched from RSU and and the reception can be finalized.*

## 2.6 Description of Field Trials and Scenarios

The following describes the two field trials that are used as input for this chapter w.r.t. hardware, software configurations and scenarios. While this work focuses on the upper layer measurements and quantifying application layer performance in one of the field trials, both field trials generated extensive evaluation of the physical layer performance. The latter results, while not part of this work, are used as reference and input in two ways; 1) to compare the in this work contributed application layer measurements and 2) as a basis for trace based simulation used to evaluate improvements to application layer performance based on the identified limitations during the application layer field trial.

### 2.6.1 Upper Layers Field Trial Overview

Based on ITS World Congress 2012 publication[4] and *ROADSAFE* deliverable D2.4 [19].

The main focus of the application layer field trial is to evaluate bi-directional, unicast based communication and interaction between the OBU and RSU. To evaluate this we consider the following scenario: A vehicle is traversing the RSU populated road infrastructure illustrated in Figure 2.6 and downloads various sizes of payloads using DTN. This use-case mimics a user scenarios for accessing detailed traffic information, route recommendations etc. Specifically, in this scenario we consider a vehicle that is informed about an upcoming event and wishes to download additional information, represented by an image of the upcoming event.

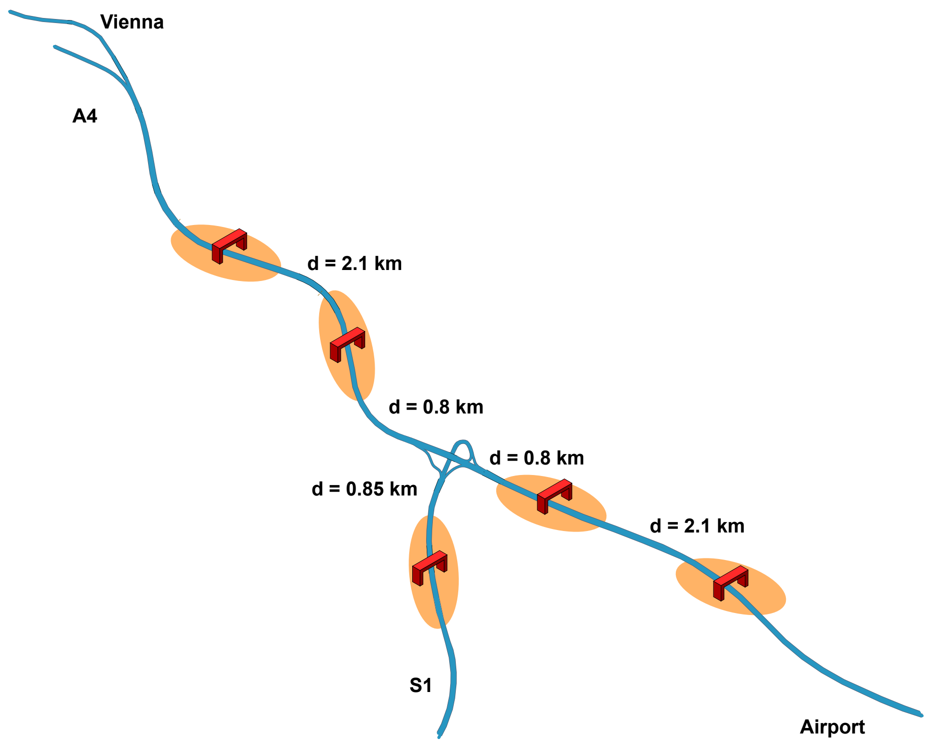


*Figure 2.6: Location of the five test RSUs on motorway A4 and S1 in Vienna, Austria.*

Figure 2.6, shows the topology of the RSU network along the portion of the motorway that was used for the field trial. Using multiple RSUs allows to identify differences in performance over individual RSUs as well as the main functionality of DTN, i.e., vertical handover over multiple RSUs.

The following sections describe the hardware configuration and the software architecture. As the DTN concept was described in Section 2.5, the focus of the software architecture is on the implementation and additional components needed to realize the field trial measurements.

### Architecture

Each RSU is equipped with an Industrial Personal Computer (IPC) connected via Ethernet to an 802.11p compliant modem prototype. The test vehicle is similarly equipped with a laptop that is connected to an 802.11p compliant modem. The hardware and software architecture that is used for field trial measurements is illustrated in Figure 2.7.

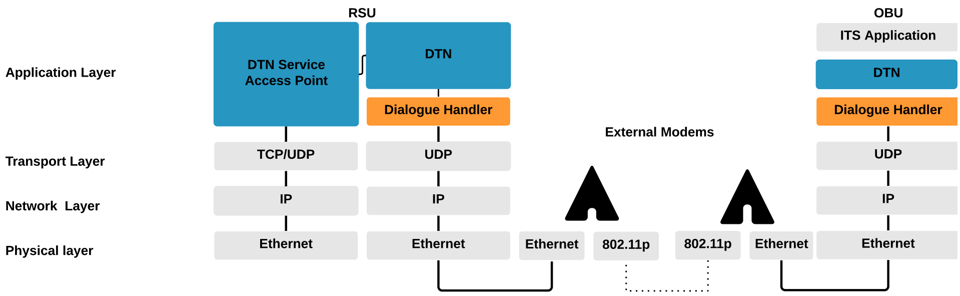


*Figure 2.7: Architecture overview. Orange boxes represent DTN modules and blue show the dialogue handler needed to support the communication. The communication between the host computer and the external modem is facilitated through an UDP connection. The modem implements a full UDP/IP communication stack that has been omitted.*

The 802.11p modems implement the 802.11p MAC, including channel switching at a 50 millisecond interval, and operate based on the exchange of WSA and WSM messages. Reception of WSA messages, which are broadcasted by the RSU periodically, is used by the OBU modem to detect the presence of the RSU, and triggers the channel switching at the OBU between the CCH and the SCH that is specified in the WSA at the appropriate time intervals. When the modem receives a WSA, the modem informs the laptop about the detection of the RSU and how to address the RSU, i.e., its MAC address and on which SCH[3] it operates.

Data exchange between the RSU and the OBU is done through WSMs messages. Each WSA message consists of the WSA payload, of up to 1400 bytes and the WSA header, primarily consisting of the destination address, i.e., the MAC address of the RSU for unicast communication or the broadcast address for broadcast communication. Each WSA message can be configured w.r.t. the transmission power and which channel is has to be sent on. The latter allows applications to define whether the message is sent on the SCH or the CCH. To trigger the transmission of a WSM, the host laptop sends a UDP message to the modem containing the application payload and the WSA meta data, specifying

[3] In WAVE a service ID is used to identify which service is provided on the specified channel. Since only one service is considered here, i.e., DTN, this information is omitted.

the WSM's parameters: Channel, destination address (MAC) and, in the case that unicast mode is used, the number of retransmissions. The transmission of the WSA content of each UDP messages is confirmed by the modem through an application layer acknowledgement to the host laptop: In the case of broadcast the modem confirms the transmission of the WSM, while the confirmations of WSA messages sent using unicast mode in addition include a) whether the message was received by the destination, i.e., if the modem received a MAC layer acknowledgement from the RSU and b) the number of MAC layer retransmissions used to deliver the message.

Table 2.1 shows the PHY and MAC-layer configuration of the modems.

| Variable: | Value: |
|---|---|
| **Modem Configuration** | |
| Data rate: | 6 Mbit/s |
| Frame size: | 1400 bytes |
| Power: | 17 dBm |
| Unicast retransmissions: | 11 |
| WSAs necessary | 1 |
| **DTN Configuration** | |
| Time-out | 2 seconds |
| **Application Configuration** | |
| Payloads | 30, 50, 70, 200, 500, 1000 kbytes |

*Table 2.1: Modem and DTN Middleware parameters*

The next section discusses the dialogue handler, which operates as an interface between the modem and the DTN middle ware, as this is not part of the DTN functionality.

### Dialogue Handler and Modem Interaction

The communication between the DTN middle-ware and the modem is realized through the dialogue handler, that operates similar to UDP; it provides an interface to send to a specific destination address, in this case the MAC address of the RSU. Contrary to UDP, it only allows a payload of up to 1400 byte, so it can fit in a WSA frame. It then forwards the data and populates the WSM meta data as needed so the message can be processed by the modem. The DTN middle-ware sends the DTN request, query or the fragmented payload to the dialogue handler and it makes sure that it, if possible, is delivered to the specified receiver. In addition, it maintains the state of the connectivity, i.e., when a WSA message is received, to initiate or resume communication.

As both the dialogue handler and the UDP connection between the host computer and the modem impact the performance, these delays are quantified as part of the upper layer results in Section 2.7.3.

### Physical Layer Scenario

The architecture and implementation was also used for a set of physical layer field measurements, which are used as a reference to the application layer field trial measurements. However, rather than using unicast, the scenario focused on I2V, broadcast mode communication only. Thus, the dialogue handler was configured to feed the modem with broadcast messages to be sent on the CCH. The broadcast scenario means that there is no overhead for initialization of the communication and all messages are continuously broadcasted by the RSUs; the vehicle records all the correctly identified messages and, with the trace from a Global Positioning System (GPS) device, their position. An incremental sequence number, embedded in each message, is then used to determine the Frame Success Ratio (FSR) as a function of distance. It should be noted that the physical layer measurements were only executed at four of the five RSUs.

## 2.7 Field Trial Results

This section presents and discusses the upper layer field trial results. The results are split up in three parts, following a top-down approach; starting with the application layer performance measurements. These results give insights into what type of applications and services are realistic to provide in the evaluated environment. We decompose these results into the elements that have an impact on the performance, e.g., DTN implementation specific sources and assumptions that generated bottle-necks and parameters specific to communication channel utilization and performance. We use the physical layer measurements, that were performed using the same field test setup, as a comparison, to support the performance evaluation.

The metrics that are evaluated are defined below, each referencing where the metric has been measured in the architecture shown in Figure 2.8. The exact definition of *how* each metric is measured is detailed when the metric is used later on.

- E2E application layer delay – The time experienced by the application from when the request is created, until the data is fully received and is available at the OBU. See measurement point A. It is defined by the following sub-metrics:
  - Total completion time – This is the time from when the request is created until the payload has been received. See measurement point B.
  - Active communication time, defined by the time during which the OBU and the RSU communicate actively. See measurement point B.
  - Waiting time, which is caused by e.g., the travel time between RSUs and the recuperation from interruptions. See measurement point B.

- Communication resource utilization – This is measured as the data volume received per RSU passing, compared to physical layer measurements. See measurement point A. Utilization, or lack there-off is further explained by:
  - Number of recorded interruptions within the communication range of the RSU due to packet loss and the duration of consecutive, successfully delivered frames. See measurement point C.
  - The delay introduced by caching (reading and writing) of the remaining payload as a results of detected interruptions. See measurement point D.
- Application layer good-put – This is measured during the active communication interval mentioned above, showing how well the channel was utilized, using measurements from the physical layer field trial as a reference. See measurement point B. The results are further quantified by:
  - Per-frame reliability improvement as a function of the number of MAC layer retransmissions. Retransmissions consume communication resources, but can, in the context of the evaluated DTN mechanism, reduce false negative w.r.t. the OBU leaving coverage. See measurement point E.
  - Inter-frame delay caused by test hardware – Has an impact on the amount of frames that can be transmitted during each SCH interval. See measurement point E.
  - Inter-frame delay caused by test software implementation – Similar as above, but caused by the software implementation and processing delay. See measurement point F.

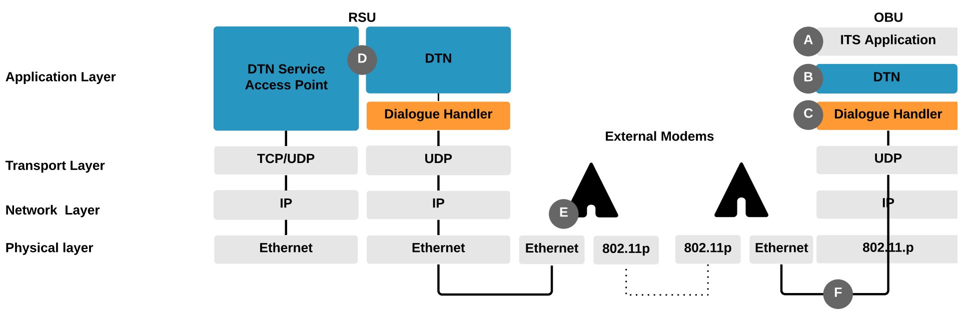


*Figure 2.8: Layered architecture overview with measurements points.*

### 2.7.1 End-to-End Application Layer Communication Delay

This section presents the measured application layer E2E delay, i.e., the duration of receiving a specific payload, and how this delay is distributed. The results are used to identify the ratio between communication time and the total delay, as this is an indicator for *how* delay tolerant applications must be. The metrics considered here are defined below:

- **Total completion time** is measured from the time the application creates an request until the requested payload is successfully received by the OBU.
- **Waiting time** is the sum of time intervals during which the vehicle is not communicating with the RSU, excluding the time between when the DTN layer on the OBU receives the request from the application until it successfully delivers the request to the RSU, i.e., when encountering a RSU.[4]. It consists of;
  - The payload request processing – I.e., from the request is sent to the RSU until the first frame of the payload has been received.
  - The payload query processing – I.e., from the query has been sent to the RSU until the communication has been resumed.
  - Time-out while being in coverage, as reported by the modem, but never the less detecting a break in the communication, i.e., due to the RSU considering the vehicle being out of communication range.
  - The travel time of arriving to the following RSU, where the communication can be re-initiated.
- **Active communication time** is the sum of durations of when the RSU and the OBU communicate actively, as seen from the DTN layer on the OBU, measured over all consecutive frame for which an MAC layer acknowledgement is received by the OBU. Further performance investigation is done in *Communication Resource Utilization*.

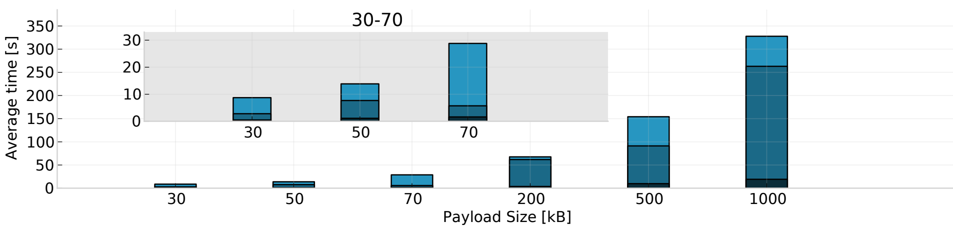


*Figure 2.9: Average time consumed in the three intervals as a function of the payload size. Black, dark blue and light blue represent communication, waiting and total completion time, respectively. The box provides a zoom in on the payload sizes from 30 to 70 kilobyte.*

Figure 2.9 presents the average duration of the three considered intervals, for six different payloads, showing that for all payload sizes between 90% and 95% of the complete

[4]Note that this means that if the application layer request was generated outside of the coverage of a RSU this time is not included, but is included in the total completion time.

time is spent without communication. The high ratio between the duration of waiting and communication intervals is a significant limitation with regards to the payloads that can be exchanged by an intermittently covered road infrastructure. Payload sizes that are relatively larger than the available communication resources of individual RSUs risk never to be completed. While cached vertical handover through e.g., DTN allows a communication session to be finalized eventually, caching data for a significant number of vehicles for a significant duration could be infeasible due to the increased hardware costs. These results emphasize that application that depend on spatially distributed access point networks should be designed such that the data is proportional to the amount of communication resources available.

It should be emphasized that the presented measurements are based on a relatively dense RSU density. This means that both the total completion time and parts of the waiting time measurements that are influenced by the density of RSUs, can be expected to vary depending on the distance between the RSUs and the speed of the OBU. This means that these two metrics are *optimistic*.

### 2.7.2 Communication Resource Utilization

Here we investigate the utilization of communication resources expressed as the total data volume received per RSU passing at the application layer. These results are compared to the data volumes received during the physical layer measurements for reference. The discrepancies between the two results are explained through an analysis of the number of interruptions experienced, identified by the lack of a MAC layer acknowledgement that DTN used to recognize out-of-coverage events, and the delay in communication they caused, thus explaining one of the causes for the waiting time presented before.[5]

In both evaluations, the data volume is calculated as the sum of all *correctly* received frames during one pass of each RSU, as reported by the MAC layer, i.e., the modem, and scaled up with the same sized application layer payload. Although the application layer measurements use unicast and the physical layer measurements use broadcast for communication, the main reason for the measured difference is caused by the RSU pausing the communication due to believing that the OBU has left the coverage area, thus delaying the communication. MAC layer retransmissions and acknowledgements are not included based on the assumption that given the same conditions neither unicast or broadcast messages would be successfully received. In addition, as the same software (link handler) was used in both field trial measurements, inter-frame spacing of transmissions by the modem is comparable for both unicast and broadcast mode as the spacing is dominated by

[5] Travel time between RSUs is the other cause, not considered here.

the communication delay between the host computer on the RSU, rather than MAC layer acknowledgements, as we will further document later on.

Table 2.2 shows the comparison between measured application layer data volume and the physical layer data volume from [20], for four of the five RSUs.[6] The relative difference is shown in the last column. Comparing the total *sum* of data received per RSU pass, the application layer measurements show a drop of either 32-37% or 71-77%, depending on RSU. Thus, the application layer was not capable of fully utilizing the available communication resources. These results also indicate that the physical layer measurements are not representable for interactive communication. To explain this discrepancy we investigate the number of false negatives the RSU experience, and the resulting delay, due to caching of the payload, because the RSU believed that the OBU was out of coverage.

| RSU | Physical Layer [Mbit] | Application Layer [Mbit] | Difference [%] |
|---|---|---|---|
| RSU1 | 12.62 | 2.93 | -77 |
| RSU2 | 10.11 | 6.36 | -37 |
| RSU3 | 11.87 | 3.44 | -71 |
| RSU4 | 13.66 | 9.28 | -32 |

*Table 2.2: Comparison of the per-RSU average received data volume of physical layer and application layer measurements.*

### Quantification of Interruptions

While DTN is designed to cope with inter-RSU interruptions, infra-RSU interruptions cause a reduced utilization of the available communication duration due to a) the time-out detecting the interruption postpones any action that the vehicle can take to resume the communication and b) the delay due to caching and reading of content. This section presents the observed infra-RSU interruptions and quantifies them w.r.t. the observed number per RSU. We also measure how the interruptions are impacting the duration of communication sessions (uninterrupted), measured as the number of consecutively correctly received frames.

Figure 2.10 shows the distribution of interruptions registered per RSU pass for each of the five RSUs, showing that for all except one RSUs the number of interruptions is significant; around 20% of the RSU passes registered more than 20 interruptions. RSU number 5, identified by the black curve, experience up to 7 interruptions per pass.

Figure 2.11 shows the average number of interruptions as a function of the requested payload size. The number of interruptions is high as even with the smallest payload size,

[6] No physical layer measurements were done on RSU 5.

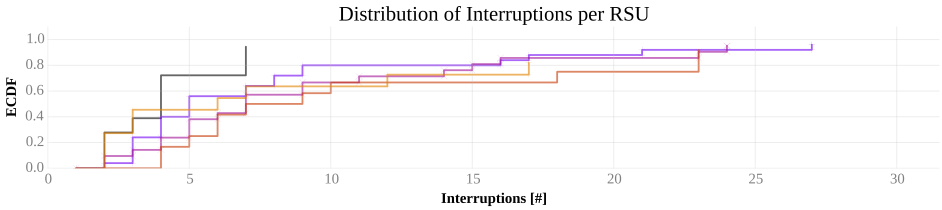


*Figure 2.10: Empirical Cumulative Distribution Function (ECDF) of the observed number of interruptions per RSU pass per RSU. The outlier (black line) is RSU number 5.*

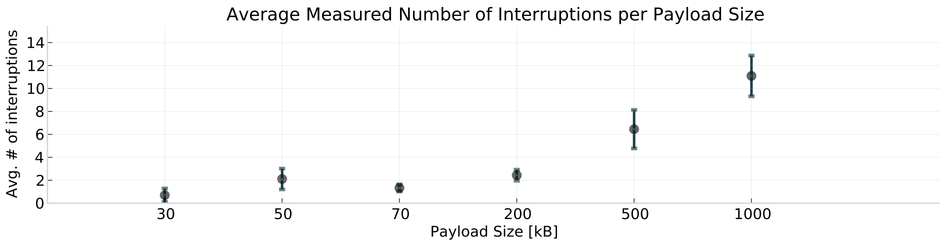


*Figure 2.11: Plot of the average number of interruptions for different payload sizes, including 95% confidence interval.*

interruptions are observed, resulting in a significant performance loss due to the time-out used to detect an interruption. Payload size over the number of interruptions corresponds to, on average, between 15 to 80 kilobytes per communication session before the sessions is interrupted, depending on the payload size. The distribution of consecutive successfully delivered frames per communication interval, i.e, before it stopped due to an assumed interruption, is illustrated in Figure 2.12. Here we see that the per RSU performance varies between 40%-80% for all sessions that consist of less than 100 frames.

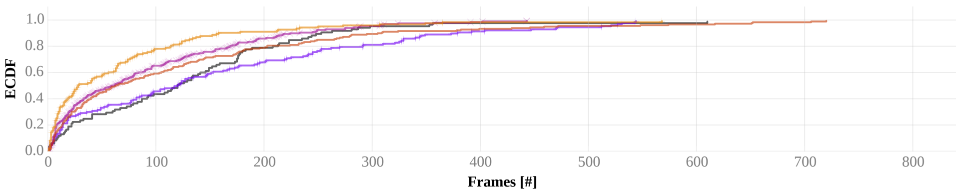


*Figure 2.12: Distribution of consecutive successfully received frames per communication sessions.*

The number of interruptions per payload and per RSU and the limited number of consecutive successfully received frames show that using the lack of a positive MAC layer acknowledgement as an estimator for whether the vehicle has left the communication range of the RSU results in a significant number of false negative (the OBU is still within reach, but the RSU believe its is unreachable). Therefore, there is a need for a more appropriate method for determining when the two nodes can (or should) no longer communicate while at the same time is less sensitive to short, intermittent durations of high packet loss.

### Duration of Caching and Retrieving of Payloads

When the DTN communication session is interrupted, the data has to be cached in the SAP responsible for the given communication session. Similarly, when the vehicle sends a query to the RSU to re-initiate the session the remaining data has to be fetched from the SAP. Both operations have an impact on the utilization of the available communication resource as they introduce a delay in the communication. This section presents the measured impact of these two operations. Because we use a time-out of two seconds before the OBU reacts to an interruption in the communication while still receiving beacons from the RSU, thus still being considered as being within communication range of the RSU, the caching of data is negligible in the presented results. If, however, a lower time-out value is considered, one that prioritizes the utilization of the potential communication duration, the delay would both include the caching and the retrieval of the data.

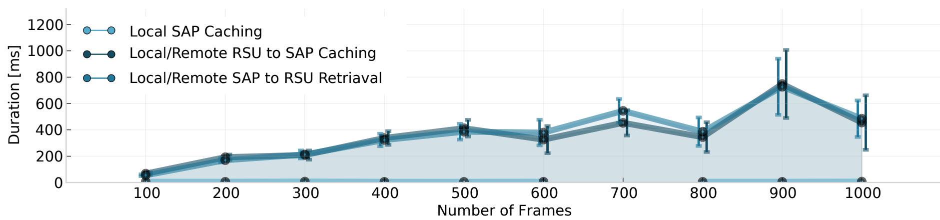


*Figure 2.13: Average duration of caching and retrieval of remaining (unacknowledged) frames of payload as a function of the number of frames. The 95% confidence intervals have been moved slightly to the left and right of the actual $x$-value to avoid overlap.*

Figure 2.13 shows the measured duration of caching and retrieving data for various payload sizes. The results show, as would be expected, that as the amount of data increases, so does the duration of read and write operations. The magnitude of the retrieval is a significantly limiting factor, especially combined with the number of interruptions presented in the previous section; each interruption is penalized by between 0.1 and up to around 0.7 seconds, depending on the amount of remaining frames. For larger payloads and a high amount of interruptions, the majority of the available communication duration can risk to be spent on retrieving the payload.

An obvious improvement is to postpone remote caching of the data to the SAP until the confidence is high that the vehicle has left actually left the communication range of the RSU, e.g., using the beacons from the vehicles that contain the vehicle position as an indicator. Rather the data could be cached locally, as this is an rather inexpensive operation, as shown in the 'Local SAP Caching' in Figure 2.13.

### 2.7.3 Application Layer Good-Put

Good-put shows the application layer communication performance, i.e., excluding retransmissions and header overhead, over the active communication time. This allows to exclude travel time and the previously discussed delay introduced by interruptions, and focus on the limitations in communication performance. Therefore, good-put is defined as follows, and measured at the receiver, i.e., the OBU:

$$\text{good-put} = \frac{payload}{\sum_{i=1}^{P} t_i} \tag{2.1}$$

where $payload$ is the size of the fully received payload. $t_i$ is the duration of the $i$th active communication interval, as defined previously, out of a total of $P$ intervals that were necessary to fully download the given payload. As mentioned in the previous section, $P$ is measured from the first and the last correctly received frame. While this allows for measuring the good-put *independent* of the RSU distribution and processing delays, it does include the CCH duration during which no data is exchanged.

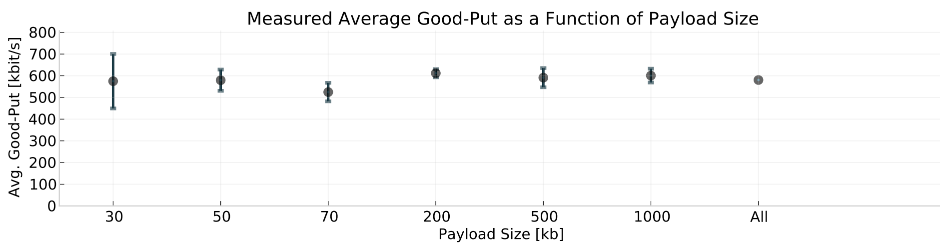


*Figure 2.14: Average and 95% confidence interval for the measured good-put for different file sizes.*

Figure 2.14 shows the slight variation of good-put over the different payload sizes and an average over all collected samples. The confidence interval for smaller payloads is impacted by the lack of communication during CCH intervals, which has a relatively larger impact on small payloads than large payloads. The most noticeable result is that the measured good-put is a factor ten less than the configured, theoretical, data rate, as it is influenced by the following factors:

1. The channel switching between SCH and CCH that, as a minimum halves, the data rate. Frames that overlap between two intervals are also lost, further reducing the good-put.
2. A unexplained performance drop during the SCH, further documented in Section 2.7.3, resulting in the SCH not being fully utilized.
3. The UDP communication link between the OBU and the external modem adds an additional delay in the inter-frame spacing, as documents in Section 2.7.3.
4. Using unicast mode, results in communication overhead in the case of retransmissions. This is further documented in Section 2.7.3.

To add context to the good-put results, we compare them to the physical layer measurements achieved using the same RSU infrastructure and configuration and to measurements performed under static conditions in a laboratory experiment. The physical layer measurements are reproduced based on [21] in Table 2.3, side-by-side with the results from the application layer measurements as well as the difference between the two. The headlines in the table are explained as follows, with indication of which numbers were taken from [21]:

- Range [m] – Range is measured from the first location to the last location where the FSR reaches 25% and goes below 25%, respectively, accordingly to the path the vehicle drives by while passing the RSU, as defined in [21].
- Phy [Mbit] – Defines the data volume received by the vehicle averaged over all RSU passing when using broadcast communication. [21].
- Phy [Mbit/s] – Defines the estimated through-put, using $\frac{\text{Phy [Mbit]}}{100km/h}$.
- App [Mbit/s] – Measured during the field trial and average over all RSUs, with mobile nodes at variable proximity and using unicast mode for communication. From Figure 2.14.
- Lab [Mbit/s] – Measured in a laboratory setting with static nodes in close proximity using broadcast mode as in the physical layer measurements.

Comparing the average physical layer and application layer through-put in Table 2.3, shows a 15.6% difference, primarily resulting from retransmissions, header overhead and the additional processing of messages in the case of application layer measurements. This leads to the conclusion that the communication intervals the channel was well utilized. However, neither results are comparable with the laboratory results, which were done under optimal conditions, showing that laboratory evaluation can results in a significant overestimation in the performance.

| RSU | Range [m] | Phy [Mbit] | Phy [Mbit/s] | App [Mbit/s] | Lab [Mbit/s] |
|---|---|---|---|---|---|
| RSU 1 | 241 | 12.62 | 1.45 | | |
| RSU 2 | 547 | 10.11 | 0.51 | | |
| RSU 3 | 584 | 11.87 | 0.56 | | |
| RSU 4 | 824 | 13.66 | 0.46 | | |
| Avg. | 592.4 | 12.092 | 0.69 | 0.59 | 2.0 |

*Table 2.3: Comparison between field trial physical layer, application layer and laboratory physical layer through-put measurements. Physical layer field trial measurements are taken from [21]. Note that per-RSU measurements are not available for neither application layer nor laboratory measurements.*

### Impact of Channel Switching

Channel switching effectively halves the through-put, but laboratory measurements showed that the SCH was not fully utilized either, having an impact on the measured through-put and good-put. Figure 2.15 shows the transmitted frames over time during the SCH interval, and a periodic interval of between 10-15 milliseconds without any communication. This results in an additional reduction of the achievable through-put of an estimated 30-35%.

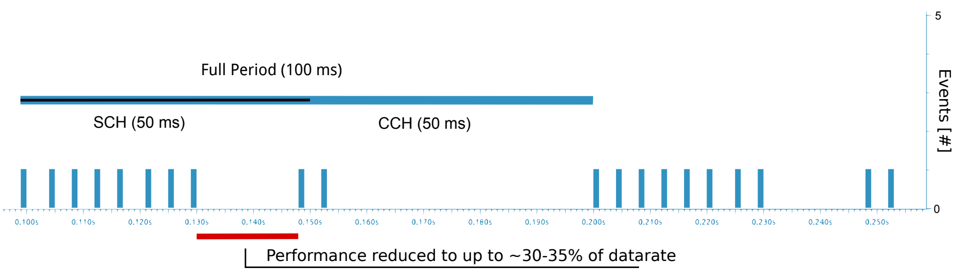


*Figure 2.15: Wireshark trace of UDP messages from the laboratory computer to the 802.1p modem, showing SCH and CCH as well as periodic intervals during the SCH where no communication occurs.*

Another thing that can be noticed in Figure 2.15 is the relatively large inter-frame spacing, which is caused by the test architecture, and further reduces the measured good-put. This is further documented in the next section.

### Processing Delay

As the measurements are based on a distributed setup where the DTN logic was running on a dedicated computer and using an external modem for the communication, some of the networking logic had to be implemented in the Link Handler module. This results in a communication and processing delay that contributes to the inter-frame spacing on the channel. The Link Handler works through a request-response approach: For each message, containing the payload to be transmitted over the wireless link, the Link Handler sends an UDP message to the modem and waits for a confirmation that the message has been transmitted by the modem. The confirmation message has to be processed before the next message can be sent by the Link Handler. The measurements presented here are measured as the delay between the host computer receives confirmation from the modem and until the next message is sent by the Link Handler to the modem.

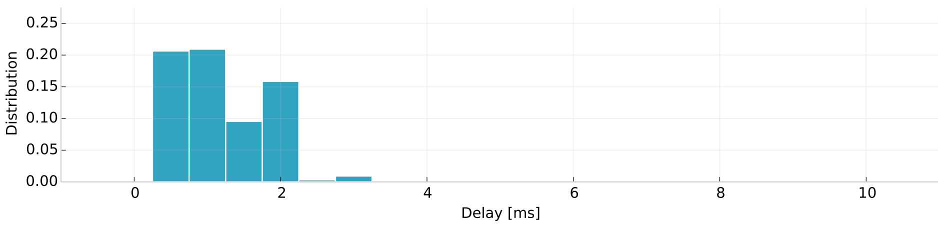


*Figure 2.16: Histogram of processing delay of the Link Handler, measuring the time between receiving a confirmation messages from the modem until the link handler sends its own message. Bin size is set to 0.5 ms.*

Figure 2.16 shows the measured processing delay distribution of the *Link Handler Module*. While the majority of the results are around 0.5-1 milliseconds and up to 2 milliseconds, considering that a 1400 byte payload transmission on the wireless channel has a duration of around 800 microseconds, it means that the processing delay reduces the channel utilization by at between 25%-50%.

### MAC Layer Retransmission

In this section we discuss the MAC layer retransmissions and how they improve frame delivery. In the current design of DTN, the successful delivery of an application layer message is of particular importance as both the OBU and the RSU use this as an indicator for whether they still are within communication range of each other. This approach is overly sensitive to packet loss, as a single message loss triggers costly overhead with regards to pausing the communication session and caching of the undelivered data, a topic further discussed in Section 2.7.2.

The result here are measured at the 802.11p modem: For each sent message, the modem provides information about a) whether the message was acknowledged on the MAC layer and b) the number of retransmissions used. The number of retransmission was configured to the maximum allowed value, 11, in contrast to the default value of 7. This was done to reduce the impact of frame loss and reduce the number of interruptions perceived by the DTN mechanism.

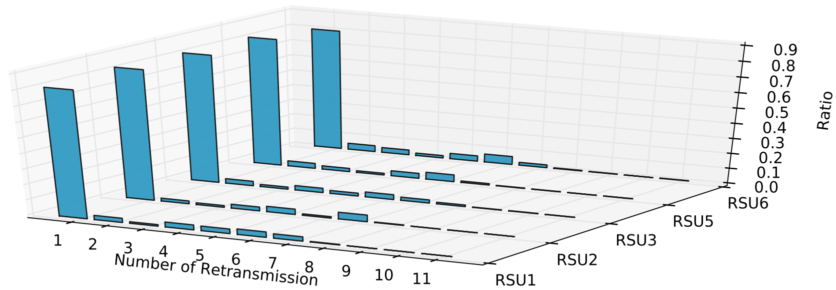


*Figure 2.17: Histogram showing the distribution of the number of retransmissions used to delivery a frame, for each of the five RSUs.*

Figure 2.17 shows the distribution of the number of retransmission used for delivering a frame, for each of the five RSUs. The results show no significant difference between the five RSUs, and the majority of the messages were delivered within the first try.

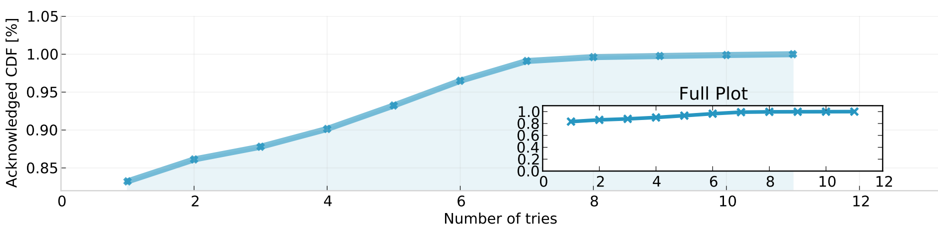


*Figure 2.18: Empirical cumulative distribution function for number of retransmissions for positive acknowledgements for all RSUs*

Figure 2.18 shows the empirical cumulative distribution for all RSUs. Interestingly, the delivery probability plateaus after seven retransmissions, the default retransmission value defined in IEEE 802.11 [22]. The RSU specific and average percentage of undelivered frames, i.e., marked with a negative acknowledgement by the modem, is document in Table 2.4, showing that on average, around 99% of all messages are successfully delivered.

| RSU: | RSU 1 | RSU 2 | RSU 3 | RSU 5 | RSU 6 | Average |
|---|---|---|---|---|---|---|
| **Successfully delivered [%]:** | 99.28 | 99.41 | 99.84 | 99.02 | 98.74 | 99.06 |

*Table 2.4: Percentage of successfully delivered frames of all sent frames, per RSU and average for all RSUs.*

### 2.7.4 Summary

The results show that using a single negative MAC layer acknowledgement is not an efficient estimator for detecting whether the vehicle and the RSU can communicate with each other, leading to a large amount of false negative. As a consequence, the utilization of the communication duration is reduced as data is spent on caching and retrieving the payload instead of communication. However, even if the application layer measurements would have utilized more of the available communication resources, the impact on the relation between how the time is spent, i.e., waiting or communicating, would not change significantly, primarily due to inter-RSU travel-time. In addition, one parameter that was not measured is the recognition of *entering* the communication range, thus, the next section includes this aspect in the evaluation.

From a general point of view, seven MAC-layer retransmission were confirmed to be an optimal trade-off between communication overhead and reliability.

## 2.8 Improving Infra-Road-side Unit Performance based on Lessons Learned

The previous sections have presented the measurements achieved during the DTN field trial and identified challenges that can be expected in a disrupted and highly mobile communication scenario. In this section, we build on these observations and apply the lessons learned, resulting in an improved communication protocol that is more suitable to the vehicular environment. In particular, we introduce two modifications:

- Modify the MAC retransmission mechanism to be able to cope with short, infra-RSU interruptions – The goal is to reduce the amount of false negatives w.r.t. whether the vehicle has left the coverage.
- Introduce a local, temporary cache in the RSU, that, when an interruption is detected, can be used to store the remaining data. In case of a false negative, this allows the RSU to react faster to a DTN query, thus increasing the utilization of the limited connectivity duration.

We evaluate these improvements using I2V traces achieved during the field trial described in Section 2.8.3 through traced based simulation. As the goal is to improve the utilization of individual RSUs, we modify the considered performance metrics accordingly. This means that we use the utilization of communication resources to evaluate the improved performance. This section consists of four parts;

- Presentation and discussion of the two modifications to the MAC layer and DTN and their motivation.
- Discussion of the traces, assumptions and processing needed to make them usable for trace based simulation.
- Quantitative evaluation of the traces w.r.t. the number of interruptions, as we need to make sure the recreate the challenges observed in the DTN measurements.
- Trace based simulation and comparison of the original and improved versions of DTN.

### 2.8.1 Revised Media Access Control Layer Protocol

The DTN performance suffered from short, intermittent *areas* where communication was poor, and the MAC layer retransmissions did not suffice to avoid packet loss, which in our case is interpreted as the vehicle driving out of the communication range of the RSU. Therefore, we modify the MAC layer retransmission scheme to distribute unicast based I2V and V2I messages in the spatial dimension, thus expecting to avoid communicating in areas with low delivery probability. The contention window is calculated such that the vehicle progresses a certain distance before attempting again. When the contention window timer runs out, the RSU tries again to send the message. For each failed attempt the timer is doubled until the arbitrary value of 10 seconds is exceeded.

### 2.8.2 Revised Disruption Tolerant Networking Protocol

False negatives, when identifying whether the vehicle has left the coverage range of the RSU, have been shown to have a significant negative impact on the utilization of the available communication duration, mainly due to the mechanisms that are needed to cache and, when necessary, retrieve the data before the communication session can be resumed. Therefore, the second aspect that is modified is to introduce a temporary, local in-node cache: This allows the RSU to temporarily store data locally, such that if a false negative occurs, the data is still available locally, rather than being returned to the originating SAP.

### 2.8.3 IEEE 802.11p Physical Layer Field Trial Overview

The field trial described in this section uses a the same scenario as described in the prevision section, but differs in the hardware used for the communication and the locations of the RSUs. One location, hereafter referred to as S1, consists of a tunnel sequence followed by a Line of Sight (LOS) sequence. The second location, A4, consists of open space where, unless other vehicles come in between, it is possible to achieve continuous LOS between the RSU and the OBU.

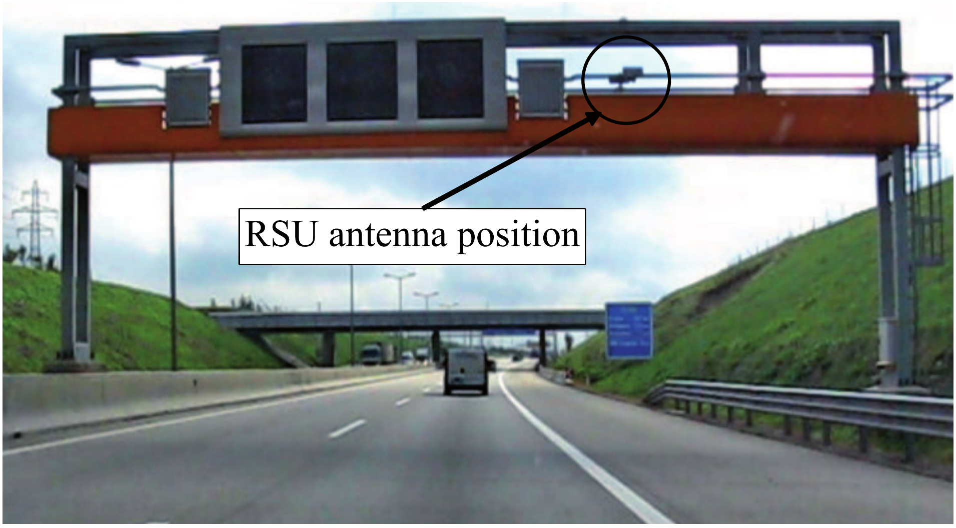


*Figure 2.19: RSU gantry position for field trial measurements.*

| Parameter | S1 | A4 |
|---|---|---|
| Data rate: | 6 Mbit/s | 6 Mbit/s |
| Frame length: | 1554 bytes | 1554 bytes |
| RSU antenna: | Pair of directional antennas | Omni-directional antenna |
| TX power: | 16 dBm | 16 dBm |
| Antenna gain: | 10 dBi | 9 dBi |
| Average speed | 100 km/h | 100 km/h |

*Table 2.5: Parameter settings for the two RSUs used for the field tests.*

While during the measurement campaign various configurations were considered; radio type, antenna and packet sizes, we are only using the traces from the configuration that yielded the best results, measured in terms of providing most data volume per RSU traversal, for each of the two measurement locations. The configuration parameters for these two traces are shown in Table 2.5. Further details and results can be found in [20].

### 2.8.4 Assumptions and Processing of Physical Layer Traces

In contrast to the DTN field trial, the physical layer field trial measured uni-directional communication from the RSU to the OBU. E.g., where the first consisted of request-response type of interaction, where the vehicle requests a payload and the RSU delivers it, in the physical layer trial, the RSU is configured to periodically broadcast messages. These message are then recorded by the vehicle as it traverses the coverage range of the RSU. As a result, the traces consists of a time series of events that indicate whether a message was correctly received or not, i.e., Cyclic Redundancy Check (CRC) Okay or Failed[7]. To use the traces to simulate bi-directional communication, we make the following assumptions:

- The channel characteristic are assumed to be reciprocal, meaning that a correctly received frame from the RSU to the OBU would also have been successfully delivered in the reveres direction, i.e, from the OBU to the RSU. Due to hardware differences and antenna positions etc., this might not be the case, however, upstream communication is only used for DTN requests and queries. These occur only on request and when an interruption is detected and are relatively smaller than the size of the actual frames used in the measurements, making this issue negligible.
- The trace does not contain acknowledgements, thus for each correctly received frame we assume that a unicast acknowledgement was generated and correctly received. Since acknowledgements are sent immediately and are significantly smaller than then data frame the impact is limited.

In addition the trace based simulation implements the following functionality:

- MAC layer emulation:
  - Realizing the CCH and SCH intervals by dividing the traces into 50 millisecond intervals.[8]
  - Simulates the reception of WSA messages, indicated by the *first* message in each CCH interval.
- Application layer (DTN) emulation:
  - Continuously generated requests as soon as the previous session is finished.
  - When using DTN, a query is issued to resume the communication sessions.

Figure 2.20 and Figure 2.21 show the MAC layer and application layer emulation graphically.

[7]Failed messages are identified through a sequence number embedded in the messages, as discussed in Section 2.8.3

[8]Similar to the DTN evaluation, WSAs are received on the CCH and the WSMs are exchanged on the SCH, respectively.

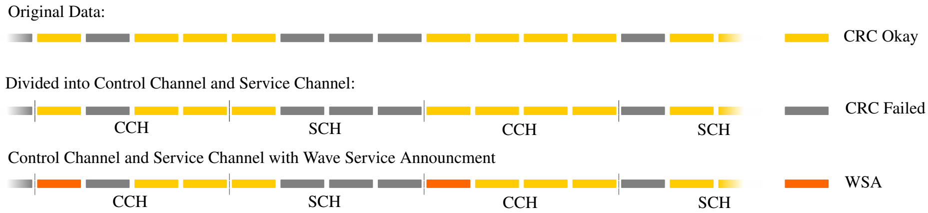


*Figure 2.20: Conversion of the original traces, containing correctly received frames, to reflect WAVE CCH and SCH switching and broadcasting of WSA messages, i.e., RSU announcements*

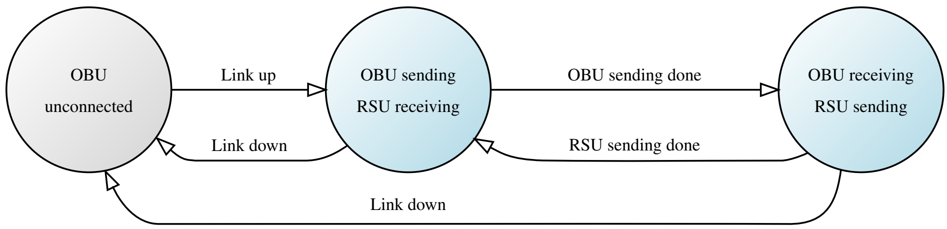


*Figure 2.21: Application layer state diagram. In order to receive data the OBU has to 1) detect connectivity and 2) send a request/query.*

### 2.8.5 Simulation Configuration

The simulation is based on three traces, corresponding to the vehicle passing the RSU three times, and the implementations of fives different protocols, i.e., one protocol that restart the communication session if an interruptions is experienced, the default DTN protocol, the two modification that were defined above, individually and in combination. Table 2.6 defines the used simulation parameters. The experiment is designed in such a way that the limitations identified in the field trial are penalized in the same way as they were penalized in the field trails. I.e., a falsely identified interruption is both penalized by having to waste time on retrieving the data, before it can be communicated to the OBU and by a two second time-out before the vehicle realizes that the connection is lost. Delay introduced by the request, i.e., retrieving the payload, has been reduced to a constant for all payload sizes such that the results are comparable across different payload sizes.

Each simulation consists of an interpretation either of three traces. To avoid synchronization over the repetitions over the same trace, a randomized offset is introduced that varies the initial point form where the trace is interpreted. To further randomize the trace interpretations, the payload size is varied in increments of 10 kilo bytes, corresponding to an additional offset of 6-7 frames in the trace.

| Parameter: | Value: |
|---|---|
| **MAC Layer Configuration** | |
| Required number of WSAs | 2 |
| Unicast retransmissions | 7 retransmissions |
| Frame size | 1450 bytes |
| **Modified MAC Layer Configuration** | |
| Contention Delay | $c * 2^{r_n}$ |
| $c$ | 10 ms |
| **Application Layer – Processing Delay** | |
| Payload size | 100 – 2.500 kilobytes |
| Request (independent of payload size) | 0.001 ms |
| Query (dependent on payload size) | See results in Figure 2.13 |
| Communication loss Time-out | 2 Seconds |
| **Simulation Parameters** | |
| Number of traces | 3 |
| Repetitions (per trace) | 10 |

*Table 2.6: Trace based simulation configuration. $r_n$ is the current retransmission number. All protocols used the same configuration, except the two contention based one, which used the modified MAC parameters.*

### 2.8.6 Simulation Results

Here we present and discuss the performance of the five protocols, using the utilization of communication resources and retransmission ratio as a metric. Figure 2.22 and 2.23 show the channel utilization as a function of payload size and averaged over all payload size, respectively. The utilization is calculated as:

$$utilization = \frac{\sum f_{used}}{\sum f_{tot}} \tag{2.2}$$

where $f_{used}$ are all frames that contributed to the payload transfer and $f_{tot}$ are all the frames that were received during all SCH intervals, i.e., that, while unrealistic, could have been utilized.

Figure 2.22 shows the communication resource utilization as a function of payload size. Little difference can be observed for small payload sizes, i.e., below 250 kilo bytes, as they do not have a high probability of being interrupted. At larger payload sizes, i.e., 1000 kilo bytes the restart mechanism gives up, as it is no longer possible, with 7 retransmissions, achieve a sequence long enough to support larger payloads. At payload sizes larger than 1000 kilobytes, the four alternative approaches also start to distinguish themselves from each other. E.g., while the default DTN approach maintains the same utilization, it suffers from false negatives and their consequences for larger payloads. While the protocol that uses the MAC layer with modified contention improves the performance by almost 35%, compared to default DTN, it is still limited by the change of the postponed communica-

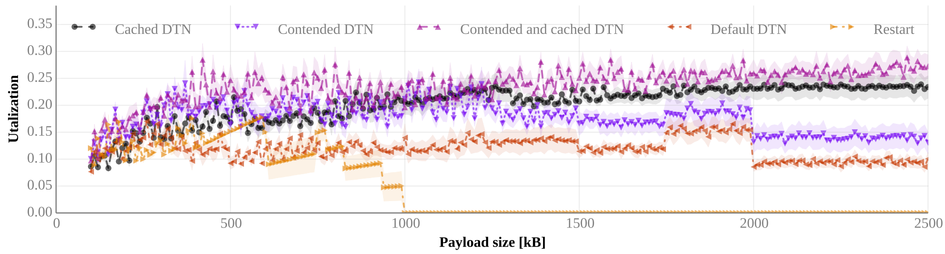


*Figure 2.22: Comparison of DTN, DTN with contention, caching and a combination w.r.t. resource utilization of communication resources as a function of payload size.*

tion synchronizing with a successfully reception event. When using DTN with temporary in-node caching, the performance improves by 50%. Combining both in-node caching and MAC with modified contention brings the improvement to 70%. For reference, Figure 2.24, shows the ratio between $f_{used}$ and the number of retransmissions, showing that the increased utilization is not caused by communication overhead, and that all modified versions of DTN improve reduce the overhead.

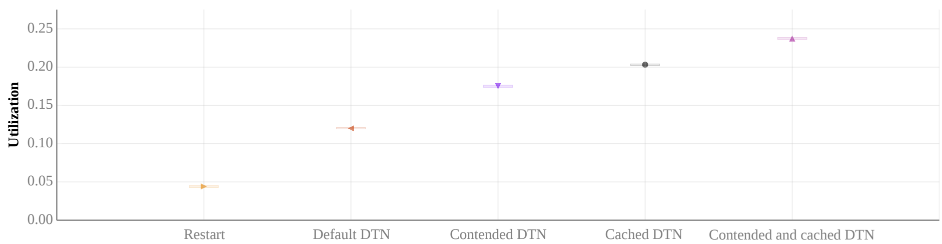


*Figure 2.23: Comparison between DTN, DTN with contention and restarting expressed in terms of successfully finished sessions (left axis) and total good-put (right axis) for various payload sizes. Upper bound reflects the case where all correctly received frames have been utilized.*

## 2.9 Conclusion

In this chapter we analyzed the performance of I2V communication based on field trial measurements, identifying the main sources limiting efficient utilization of the available communication resources. In addition, a simple DTN protocol for vertical handover between RSUs, when the communication requirements exceeded the available communication resources provided by an individual RSU was introduced and evaluated during a field trial and improved based upon the lessons learned.

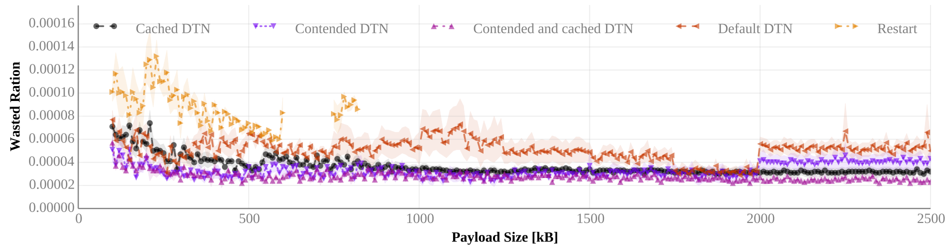


*Figure 2.24: Comparison of DTN, DTN with contention, caching and a combination w.r.t. ratio between utilization and retransmissions as a function of payload size.*

The main results show that while DTN is useful to enable finalization of payloads, e.g., small, interconnected bundles of PVD, by distributing the communication over multiple RSUs, data heavy application need to be designed with delay tolerance in mind. Given the limited communication durations, caused by mobility and channel switching, the infrastructure is best suited for information that can be communicated self-contained messages. Given the presented measurements, where application layer good-put reached around 600 kilobit per second, a high user experience should not be expected, when considering that even mobile web-sites are measured in megabytes. Another argument against large payloads is that this would significantly increases the storage capacity of the infrastructure (RSU), in order to be able to cope with temporarily caching data for all vehicles. Thus, DTN enables and is suitable for delivery of large amounts of PVD, but unrealistic for providing data heavy services to the OBU.

The main results show that while DTN is useful to enable finalization of payloads, e.g., small, interconnected bundles of PVD, by distributing the communication over multiple RSUs, the RSU infrastructure is not suitable for exchanging large amounts of data. This is due to the relatively high waiting time to communication time ratio; at 90% idle time, the total communication time would grow exponentially as a function of the payload size. Another argument against large payloads is that this would significantly increases the storage capacity of the infrastructure (RSU), in order to be able to cope with temporarily caching data for all vehicles. Thus, DTN enables and is suitable for e.g., but unrealistic for providing data heavy services to the OBU.

W.r.t. utilization of the communication resources during the pass of a single RSU, the main limitation identified was caused by variability in the communication performance, which the traditional MAC layer retransmission scheme does not handle well. The challenge being to define an appropriate mechanism that is capable of identifying when to when to attempt to re-initiate communication or decide that the vehicle is out of the communication range. For this, two methods were introduced and evaluated, namely a modified MAC layer retransmission scheme, that distributes the retransmissions over time such that the channel characteristic can, rather than the typical mechanism that is used to avoid congestion. The second being a local, temporary in-RSU caching mechanism, that, in the case of a false negative occurring, would still be able to resume the communication without significant delay.

The time distribution of a communication session in the context of an 802.11p communication infrastructure was show to spend significant time in idle mode, either due to inter-RSU travel, or recovering from interruptions. This idling is an indicator of the delay of large payloads that can be communication, and should be taken into account when an application decides which communication medium to utilize. 802.11p may be a cost effective communication platform for V2I communication, but DTN introduces significant cost increases for the storage capabilities necessary to enable it.

With regards to the lower layers, the results validate 802.11p's default retry value of seven retransmissions of unicast messages, as the contribution of additional retries do not provide significant contribution, given that 99% of delivered messages were delivered within seven retries. It was also shown that distributing these seven retires over a larger timespan than the default MAC layer contention window can help with avoiding communication attempts in regions with poor FSR. The cause for this is that by increasing showing that it is an efficient approach for detecting whether the vehicle is out of coverage, when no other contextual information is available.

## 2.10 Future Work

The results for DTN show a significant potential for improvement by allowing more intelligent communication strategies and application of accurate data exchange prediction. The first topic is motivated by the results that a significant number of initial data exchanges failed when the initial request was lost due to low FSR even though the initial trigger from the modem about being in coverage has been received. The unnecessary fetching and storing of data motivate the second topics, where estimation could improve 1) the amount of data which is being fetched to reflect what is actually possible to deliver and 2) avoiding unnecessary remote storage due to interference.

### 2.10.1 Reliable Detection of Road-side Unit Coverage Islands

One of the main challenges was to correctly identify interruptions as being caused by interference or due to a vehicle leaving the coverage area for permanently. As the vehicle know its own position and the RSU announcements, at least in the ITS-G5 case, contain the position of the RSU, it could be possible for the OBU to correlate the lack of communication and the positional information to decide which is the case.

Communication performance maps, e.g., as defined in [23] and the derivate discussed in Chapter 5, can be used to improve communication performance through scheduling the communication as a function of the expected quality; by only utilizing communication resources in areas where the quality is high, the unnecessary consumption of resources is reduced. In the context of DTN, performance maps can be used to both estimate how much data can be transfered, how many RSUs are necessary and to schedule the communication exchange.

### 2.10.2 Reliable Communication

A limitation of the field trial evaluation is that an implementation of a communication stack which provides reliable communication was not available. Given a platform where TCP/IP is implemented, it could be paired with DTN to achieve both reliable communication during inter and infra-RSU durations; i.e., a wireless communication optimized TCP implementation could be paired with a bundling approach in which DTN fragments the payload that is expected to be communicated in either direction, each bundle being transmitted to a different RSU.

# Chapter 3

# *Properties of Probe Vehicle Data Collection*

In this chapter we evaluate how the collection delay of Probe Vehicle Data (PVD) is impacted by travel time caused by the travel distance between Road-side Units (RSUs) distributed throughout the road infrastructure. Using a realistic mobility simulation scenario and a real world map we measure the delay distribution for the considered mobility scenario w.r.t. the spatial and the overall delay distribution and evaluate how the travel distance impacts the estimation accuracy for three selected algorithms.

The content of this chapter is based on [3]. The aBox algorithm that was proposed in [3] has been simplified, and the results have been extended to include additional explanation.

## 3.1 Introduction

Road operators invest significant effort in gaining accurate and timely insight into the traffic situation of their road infrastructure. This information allows them to know how the road infrastructure is used and to identify problems such as congestions or events causing bottlenecks. While a broad range of technological solutions, such as static vehicle counters, are already deployed throughout the road infrastructure, PVD, sensor data generated by vehicles, is anticipated to contribute by increasing the level of detail and by providing information from areas where no sensors are currently available.

PVD may be categorized into two groups, event driven and periodical PVD. Event driven PVD is triggered by the vehicle detecting an event, resulting in the generation of a report. Periodical PVD is, almost, always generated and consists of sampling a specific sensor type. Using a traffic congestion as an example, event PVD includes detailed information about the location of the congestion, when it is detected, ect. Periodical PVD from the same area shall consist of speed samples generated along the congestion. Therefore, their purpose also differ in most cases; event information informs drivers of upcoming events while periodical information may provide information about the consequence, such as expected changes in travel time due to a lower speed. While the collection of both types of PVD can benefit from the same collection algorithms, their challenges and requirements, in particular non-functional requirements, differ. In this chapter we focus on the evaluation of periodical PVD generation, collection and aggregation.

The content of one periodical PVD sample typically consists of a core set of elements, being the time and the location of when and where the sample is generated, the sensor type and corresponding value. For the PVD to provide any information to the road operator, it has to be collected from the vehicles, processed, depending on the purpose of it, and then presented at the Traffic Control Center (TCC). Considering the communication infrastructure of distributed access points described in Section 1.1, in this chapter we analyze the characteristics of collecting PVD in said infrastructure and how different aggregation algorithms react to these characteristics.

## 3.2 Background, Problem Formulation, Statement and Related Work

Throughout this section we present how traffic information is currently collected and the role of PVD in this context, see Section 3.2.1. This information is used together with the infrastructure described in Section 3.2.2 to define the problem formulation and statement, w.r.t., challenges of collection of PVD through a RSU based infrastructure and state the contribution. Section 3.2.3 discusses the related work w.r.t. PVD and data stream processing. FInally, Section 3.2.4 outlines the remainder of this chapter, defining how the identified challenges are approached.

### 3.2.1 General Traffic Information Collection

Currently, one of the main sensor based sources used in traffic state information collection are various types of static, point based traffic sensors; in-road magnetic loops, traffic cameras or electronic tolling systems. These sensors count the number of vehicles passing by, identify the type of vehicle and its speed, periodically (typically every 60 seconds or 15 minutes) generating reports of the vehicle count and speed per category. These reports provide accurate estimations of the current traffic situation; [24] defines that the maximum allowed measurement error of a sensor has to be below 3%[1] for both the average speed estimation and the vehicle count. While accurate, these sensors can only observe the road infrastructure at locations at which they are installed. Due to the cost associated with the installation and maintenance of these sensors it is infeasible to monitor the entire road infrastructure. Point sensors are in most cases also not able of re-identifying vehicles over multiple locations[2], meaning that travel time cannot be measured directly and must therefore be estimated based on the collected data. The anticipated advantage of PVD is that vehicles are capable of collecting traffic telemetry data from all over the road infrastructure. This information can be used to augment the existing sensor infrastructure by

[1] 3% if the speed is above 100 kilometers per hour and 3 kilometers per hour when below.

[2] Research is however under way to remove this limitation, e.g., []

increasing the level of details; while in-road sensor can detect reduced road capacity due to congestion, PVD can pinpoint the exact location of the congestion.

An emerging approach for traffic state estimation is based on tracking of mobile devices with wireless communication capabilities as they travel through the road infrastructure. I.e., mobile network operators using their existing cellular infrastructure or third parties installing Bluetooth or Wi-Fi sensors throughout the road infrastructure. These applications are primarily used for travel time estimation between two points, flow estimation etc., as soon as specific devices are observed at two distinct locations. In the case of cellular, the main advantage is that the infrastructure is already largely available, has a high coverage and while it requires additional mechanisms for processing it has been shown to provide reliable results ([25], [26]). Systems based on collection of probe request from Bluetooth or Wi-Fi are typically inexpensive but require in most cases new equipment to be installed at relevant positions in the road infrastructure. The main limitation of external monitoring is that it can only provide traffic related data, while PVD can, theoretically, access and collect data any sensor that is available in the vehicle. Additionally, the external monitoring approaches have been specifically designed to be used for traffic information collection, and are depending on, at least in the case of Wi-Fi monitoring, a feature that is unnecessary for the device to work properly, where wireless communication devices broadcast their unique identifier. This can result in these systems becoming obsolete as privacy concerns gain more focus. For example, companies such as Apple claim [27] to randomize the Media Access Control (MAC) address, that could otherwise serve as a unique identifier, of their devices such that they cannot be traced. [28] even concludes that device tracking can be against European privacy directives, as users do not have the option to provide their consent nor can they opt-out from the data collection. In contrast, PVD is actively generated by the On-Board Unit (OBU) in the vehicle, which can allow a more fine grained control by the driver of what and if they want to contribute with their own information.

PVD can also be collected through the cellular infrastructure, using the driver's cellular data subscription. This approach is mainly driven by mobile device platforms like Android and iOS and various dedicated mobile device applications for navigation and personal tracking. These already generate and collect travel time and position information, often combined with e.g., speed, whenever the user uses the application [29]. These applications typically collect information from the user with implicit consent or by disabling their functionality otherwise if they are not allowed access. Vehicle manufactures also already equip their vehicles with cellular connectivity and collect vehicular sensor information for both traffic state collection and vehicle diagnostics. Limiting factors for these approaches are that the collection is typically done centrally rather than locally, where the information is relevant and that the collection is typically associated with a cost for usage of cellular communication. Vehicles equipped with OBUs are capable of exchanging information directly with each other, a necessity if they want to make use of safety applications. Besides that, it is anticipated that road operators roll out RSUs through-out the infrastructure that enables the dissemination of traffic information. Using this infrastructure, we anticipate to collect PVD from the vehicles such that the disseminated information can be further augmented, and if resource capacity allows, to collected any relevant sensor data information that the vehicles can provide.

At the time of writing, a large pan-European[3] corridor project is under way to deploy an infrastructure of RSUs covering the main roads leading from Vienna, Austria, to Rotterdam in the Netherlands, via Germany. The project defines applications that will be available during the various roll-out phases and the RSU infrastructure itself. I.e., data management and exchange between the TCC, RSUs and the vehicles. The project itself includes participants and stake holders from both the vehicle industry, OEM manufactures of communication equipment and road operations. The generation and collection of PVD is in this context anticipated to be part of a later phase, that still needs to be defined.

### 3.2.2 Problem Formulation, Problem Statement and Contributions

Key problems that need to be understood w.r.t. PVD collection using a spatially distributed RSU infrastructure are caused by a low number of vehicles equipped with OBUs, making them capable of generating PVD and a low amount of RSUs, resulting in high travel time from when the data is generated until it can be delivered.

Travel time delay characteristics between RSUs are mainly influenced by the RSU distribution and density. As their purpose is to disseminate and collect primarily traffic information, they can be expected to be located at key locations throughout the road infrastructure, identified by the amount of vehicles they can service. For example, to reduce congestions by distributing the vehicular traffic evenly thorough the road infrastructure, RSUs have to be located such that the drivers can be informed, have enough time to process the information and decide on how to proceed. Congestions and free flow traffic conditions also impact the delay from the time when a probe is generated and until the vehicle arrives at the RSU and delivers the probe. Especially during congestion, when the information may provide the most benefit, the travel time can be expected to increase.

Traditionally, vehicles have significantly longer life-cycles and renewal rates compared to most consumer devices. This means that the roll-out phase of vehicles equipped with OBUs can take a significant amount of time. ETSI, who defines the European ITS standards ITS-G5, estimated a 90% penetration rate of vehicle equipped with OBU to be

[3] http://eco-at.info

reached around 2030 [30]. For comparison, it took the seat-belt more than 15 years to become mandatory safety equipment for new car, while older models are still excluded.

The problem statement driving the work presented in this chapters is

and is answered with the following contributions:

- We evaluate the impact of travel time delay using three different RSU distribution, a real map and realistic mobility.
- We evaluate how the estimation of three common aggregation algorithms is impacted when the RSU density, the penetration rate and the sampling rates are varied.

### 3.2.3 Related Work

Generally, [31] defines eight rules for stream processing, i.e., the processing of continuously received data, but Rule 3 is the most applicable to this evaluation. Rule 3 in [31] defines that a steam processing system must be able to cope with the imperfection in the stream, like delay, missing and out-of-order data, and states that the system processing the data must be able to time out on missing data or postpone the processing when the data is delayed. In the PVD collection use-case, the main parameter of influence is the delay, which can be hard to predict, and must therefore be coped with. While stream processing, is a well establish research topic within many fields, the quantification of the delay characteristics in the context of PVD collection using a distributed RSU infrastructure has received little attention. We investigate how this delay behaves and how the processing is impacted.

The penetration rate of OBUs has an impact on both the probability of a vehicle passing though a given area and the amount of data that can be expected. In [32], [33] and [34] the authors argue that penetration rates between 1% and 5%, are enough to provide useful information about the urban traffic state. These numbers depend on the road type and the sampling interval, on the delivery time and interval, etc. Most existing systems for PVD collection are *pre-configured* to periodically collect speed, position, heading information and communicate it, usually over a cellular connection, to a processing center. The sampling interval is typically configured between 30 seconds and 15 minutes [35] to reduce communication and processing requirements. However, one of the aspects that we wish to investigate is the potential of increasing the sampling rate of individual vehicles, to compensate a low penetration rate, as would be anticipated during the roll-out phase of OBUs.

In [33] the authors suggest using eXtended Floating Car Data (xFCD), a message that contain *events* rather than raw sensor data. While we agree that event information could be used for detecting events, periodic PVD is needed to collect information about currently

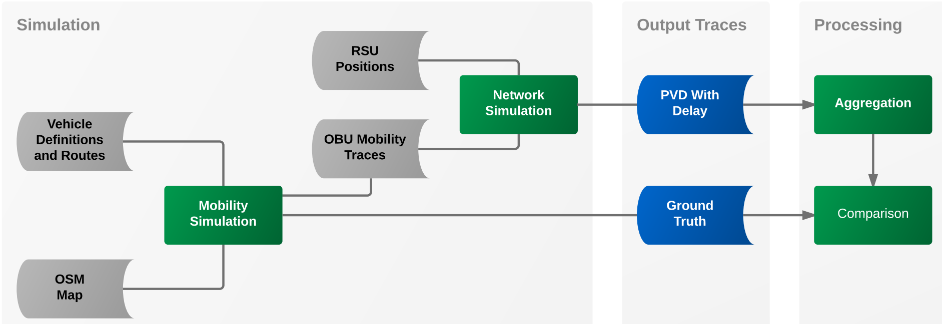


*Figure 3.1: Simulation and processing overview. Green represents simulation or processing, blue represents output data and grey the used input data.*

ongoing trends, and to provide additional information from the entire road infrastructure and the even area.

### 3.2.4 Outline

The remaining of this chapter is organized as follows. In Section 3.3 we describe the simulation environment, scenario and the high-level processing used for acquiring the data used in the evaluations later on. Section 3.4 and Section 3.5 present the travel time delay distribution and the impact on estimation accuracy of the three algorithms, respectively. Finally, in Section 3.6 we conclude this chapter.

## 3.3 Evaluation Setup

In this section we define the scenario used for both travel time measurements and the evaluation of how penetration and sampling rates impact the accuracy of different aggregation algorithms. The simulation and evaluation setup is illustrated in Figure 3.1. It consists of three steps: A mobility simulation that provides realistic vehicular mobility including vehicle following, lane positioning etc., a network simulation that applies constraints on the communication between vehicles and RSU and a post-processing and aggregation step. The latter depends on the evaluation type and is described in further details when used.

### 3.3.1 Evaluation Scenario

The considered scenario consists of a number of vehicles driving through the road infrastructure illustrated in Figure 3.2 and representing a large part of the motorway S1 in vicinity of Vienna, Austria. The road infrastructure is populated with RSUs, shown later, that are used to facilitate the collection of PVD collection from the vehicles. Depending on the configuration, a subset of the participating vehicles are periodically generating PVD. Each PVD sample consists of a time-stamp for when the probe was created, the position where the probe was created and a sensor value, being the current speed of the vehicle. Whenever the vehicle encounters a RSU it uploads all PVD elements that it has generated until that point in time. Up to 20 individual probes are aggregated into one message, before sending. RSU detection is realized by the RSUs broadcasting beacons, triggering the upload of PVD. Upon reception of the PVD, each element is considered as a self-contained entity, i.e., any vehicle identifier is stripped away by the RSU, and the RSU tags each probe with a time-stamp of when the data was received.

In the simulation we consider a total of 3379 vehicles. Each vehicle has a randomly selected start and end point, the route between the two is automatically generated using an shortest path approach. The entire simulation duration is 60 minutes, resulting in an intermediate level of traffic in this particular road infrastructure[4]. The considered motorway segment is around 16.6 km, or 33.2 km when including both directions. The road consists of 2-3 lanes, depending on the location.

RSU locations differer depending on whether we are investigating general travel time or the penetration and sampling rates, therefore these details are further described in their respective sections. For the aggregation to be able to have something to detect, an artificial congestion is created at a specific time and at a specific location.

### 3.3.2 Mobility Scenario

The mobility simulation is realized using SUMO [36], enabling us to simulate realistic vehicular mobility using an actual road network from e.g., OpenStreetMaps.org.

The mobility scenario is crafted such that enough traffic is injected into the road infrastructure such that a congestion emerges and dissolves at two distinct points in time during the simulation. This is due to the need for variability and an event has to exist that can be detected. I.e., a constant speed would not allow for measuring the reaction time of the evaluated algorithms. The considered road infrastructure is populated with vehicles using the vehicle distribution specified in Table 3.1. One generator is sued to add a vehicle every 5 seconds throughout the entire simulation, while for warm up phase, consisting of 300 seconds, the road infrastructure is flooded with 10 vehicles per second to populate the road infrastructure.

To increase realism, the randomized route generator is configured such that short road segments are prioritized and a preferred minimum route length is defined. As the considered road infrastructure is a motorway, this increases the probability of a realistic arrival and

[4]During peak hour this particular part of the road infrastructure carries around 3600 vehicles per hour in each direction. Since our simulation considers both direction, this results in slightly less than half of the capacity being utilized.

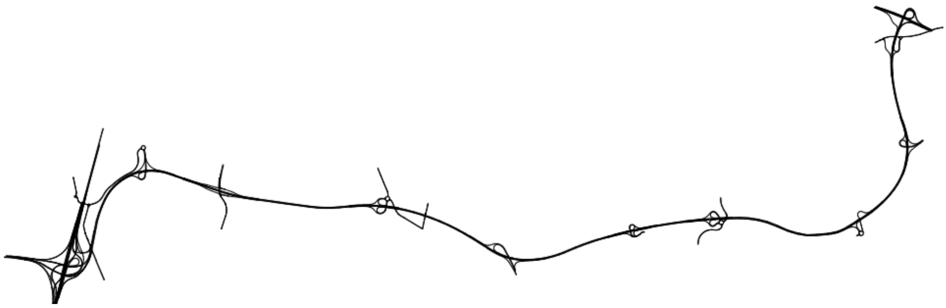

*Figure 3.2: Representation of the part of the motorway S1 near to Vienna, Austria, used for the evaluation. The particular segment consists 16.6 kilometers of road. The locations of RSUs are visualized later on.*

departure of vehicles. In addition, we vary the driver imperfection simulated to created variability in the driver behavior as defined by $\sigma$[5] in Table 3.1, increasing the probability of randomly occurring congestion.

| **Procedure:** | **Definition:** |
|---|---|
| Total number of vehicles: | 3379 |
| Simulation Runtime: | 3600 seconds |
| **Vehicle Type Distribution:** | |
| Car Type 1: | 40%, 55 m/s, $\sigma = 0.1$ |
| Car Type 2: | 50%, 45 m/s, $\sigma = 0.9$ |
| Trucks Type 1: | 10%, accel = 2 m/s, decel = 3 m/s, 50%, 20 m/s, $\sigma = 0.1$ |
| **Random Routes::** | |
| Fringe factor | 100 |
| Min distance | 12000 |
| Vehicles per second (warm-up) | 10 |
| Vehicle per second (entire duration) | 0.2 |

*Table 3.1: SUMO Simulator configuration. SUMO specific parameters: 'Fringe factor' and 'Min distance' are tweaking parameters that define how random routes are generated, $\sigma$ defines the driver inaccuracy. All parameters not mentioned are default.*

### 3.3.3 Network Scenario

The output of the mobility simulation is used as input for the NS-3 simulator. The network simulator is used to restrict the communication between the vehicles and the RSUs and to implemented the application logic in the vehicles responsible for generating, caching and uploading the PVD to the RSUs.

[5] $\sigma$ is defined in [37] as "the driver's imperfection in holding the wished speed".

To reduce the computational complexity of the simulation, certain assumptions have been made that impact the simulation of the communication. The vehicles can only communication with the RSU and not with each other. Also, the communication is reciprocal such that if a node receives as messages it can, unless significant delay is experienced and the vehicle is driving away from the RSU, be sure that a response will also be delivered. Additionally, the range propagation loss model has been configured such that the communication is reciprocal; if the vehicle is able to receive a beacon from the RSU, it can assume that a response with be delivered. Table 3.2 lists relevant NS-3 parameters that are used.

| **Procedure:** | **Definition:** |
|---|---|
| **Simulator Configuration:** | |
| Infrastructure | AdhocWifiMac |
| Phy Mode | WIFI_PHY_STANDARD_80211_10MHZ |
| Data Mode | OfdmRate6Mbps |
| Propagation Delay | ConstantSpeedPropagationDelayModel |
| Propagation Loss | RangePropagationLossModel |
| MaxRange | 300 m |
| RxGain | 25 |
| **OBU Application Settings:** | |
| Sampling Rate | 1 second |
| **RSU Application Settings:** | |
| Announcement Frequency | 1 second |

*Table 3.2: NS-3 simulation configuration. The names on the right hand side define the NS-3 models. Remaining values are default, except the modification described in the text.*

The network simulation used is overly optimistic, and is based on the assumption that reliable, low communication overhead communication protocols that enable communication between the RSUs and OBU exist, or will exist. As we focus on evaluating the properties of the probe data, the main network simulation parameter that has an impact is therefore the communication range, which is selected conservatively here (see Table 3.2).

### 3.3.4 Pre-Evaluation of the Mobility Scenario

For reference, Figure 3.3 and Table 3.3 show the number of probes received per second and in total, respectively, for each of the three scenarios used for delay estimation measurements. Figure 3.3 shows that all three scenarios receive messages through the entire time period with is considered in the evaluation. The difference in the total amount of probes shown in Table 3.3 is due to vehicles leaving the infrastructure without encountering a RSU to which the probes can be delivered when the RSU density is lower.

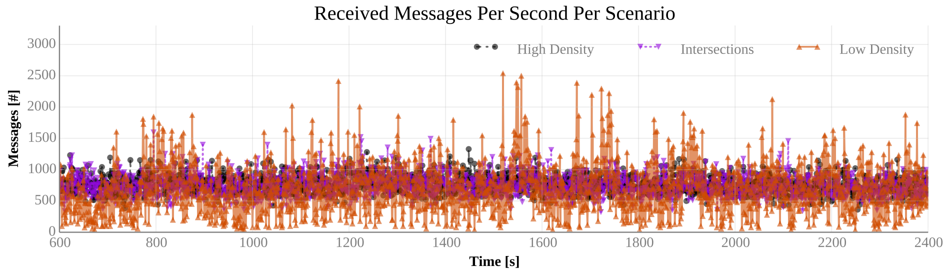


*Figure 3.3: Number of probes received per second for each of the three scenarios, averaged over all participating RSU*

| Scenario: | Total Number of Probes: |
|---|---|
| Low | 2,533,209 |
| Intersection | 2,726,271 |
| High | 2,801,855 |

*Table 3.3: Total number of messages received for each scenario*

## 3.4 Probe Vehicle Data Collection Delay

PVD collection delay is in most cases caused by the travel time between the location where the probe is generated and until it can be delivered to a RSU, by the vehicle.[6] Besides the distance the vehicles have to travel, the delay can fluctuate depending on the current traffic conditions and the driver's driving attitude. The metric that is investigated here is the general collection delay distribution of PVD, caused by the travel time. Other factors contribute to the collection delay, such as communication and processing delay, but the travel time delay is considered to be the main contributor with the highest expected variability, compared to the other two. We compare our measurements to the delay distribution of PVD collected through a cellular infrastructure. While the delay is caused by unrelated effects, it allows us to compare our results to an existing system. Before discussing the travel time delays, we describe the three RSU infrastructures that are used in the simulation to provide data for the evaluation.

### 3.4.1 Road-side Unit Infrastructure Topology

For the travel time delay evaluation, we consider the scenario described in Section 3.3 using three different RSU distributions: high, intermediate and low RSU density. The RSU locations for each of the three scenarios are illustrated in Figure 3.4. In the intermediate

[6] We wish to characterize the travel time delay here, so forwarding using other vehicles is in this case ignored.

density scenario, named *intersections*, the locations of the RSUs are selected such that all intersections are covered. In a deployment scenario, this would result in that the majority of vehicles can exchange information with the infrastructure when entering or leaving the motorway. In the case of low RSU density, referred to as low density, not all motorway exit ramps are covered. This can result in loss of information as not all vehicles have an opportunity to upload their information. In the high RSUs density scenario, RSUs are positioned at locations where existing infrastructure exists; gantries, variable message signs etc., under the assumption that this can reduce potential installation costs. The inter-RSU distance, *excluding* the radio coverage range, ranges between 800 to 1500 meters for the low density scenario, 3-5 kilometers for the intermediate density scenario and around 10 kilometers for the low density scenario. This corresponds to 30-54 seconds, 108 seconds - 3 minutes and 6 minutes travel time between RSU for each of the scenarios, when driving at 100 kilometers per hour, receptively.

### 3.4.2 Collection Delay Results

We evaluate both the delay distribution as a function of the spatial distribution of where the probes were generated, see Figure 3.5, and the delay distribution as is it observer per RSU, see Figure 3.6. We define the delay $d$ of an individual probe $p$ as:

$$d_p = r_p - g_p \tag{3.1}$$

where $r_p$ is the time-stamp at which the RSU received the probe and $g_p$ is the time stamp when the vehicle generated the probe at a given position $(x, y)$.

#### Spatial Travel Time Delay Distribution

Figure 3.5 shows the delay distribution averaged over $50x50$ meters bins, plotted over the origin of the PVD, for each of the three RSU distributions. At high RSU densities we observe an overall low delay, generally below 1 minute, except at the edge, which is caused by congestion in that area. For both the intersections and the low density scenario, we observer triangular shapes in the distributions, due to the increased travel time. The artificially created congestion is also easily identifiable at around $(x, y) = (40, 100)$, causing an almost doubling of the delay. In the low density scenario, the average delay was observed to reach around 9 minutes at certain locations.

Generally, these variations in the delay when the probes are received, caused by travel time and increased under poor traffic situation make it challenging when aggregating the data and presenting it at the TCC. E.g., the choice is whether to present *all* the data with a delay, such that a uniform status can is provided. Or, the data can be presented at it is

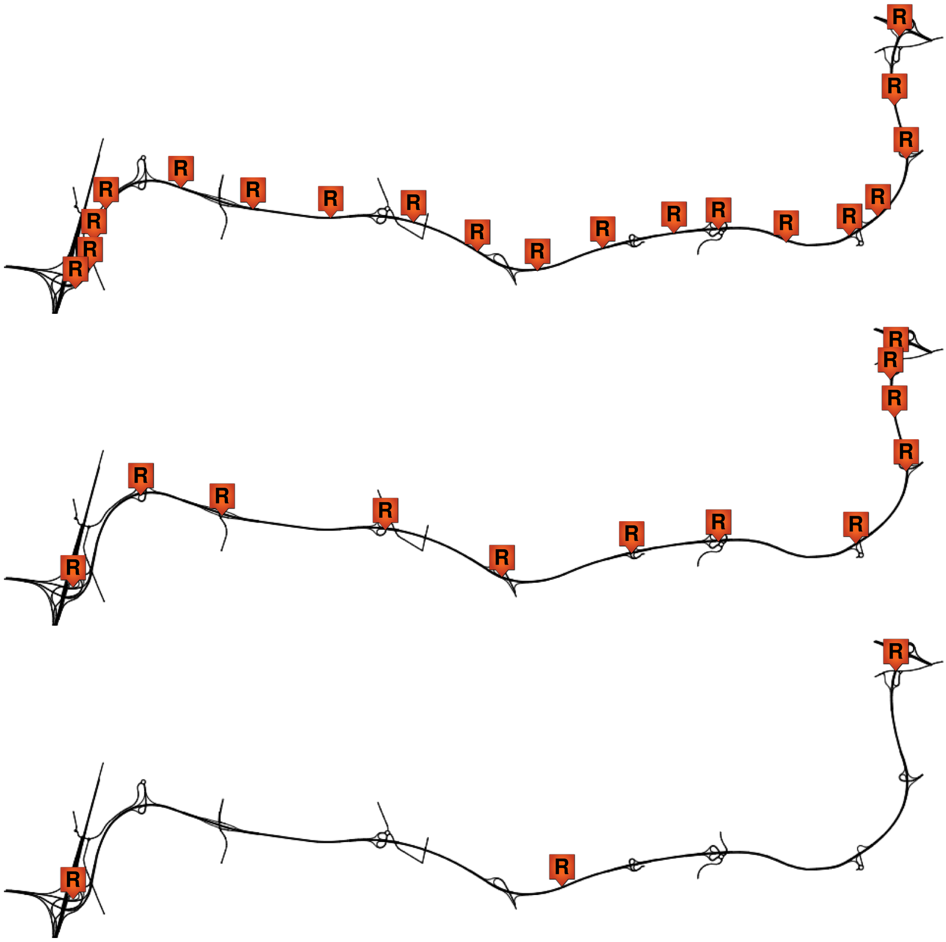

*Figure 3.4: RSU locations for each of the three scenarios.*

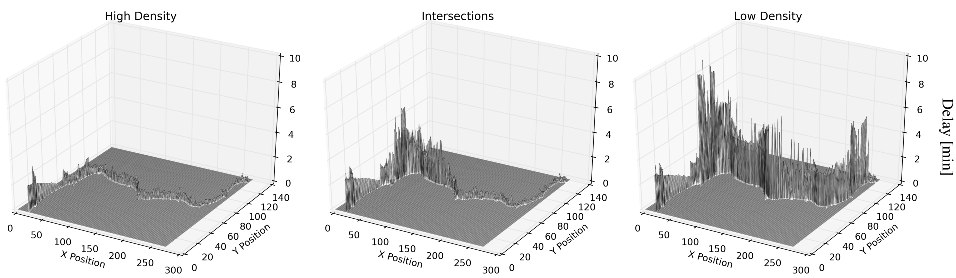


*Figure 3.5: Average delay distribution in minutes for each of the three RSU distributions. Note that $x$ and $y$-axes are scaled $1:50$, as delay values are binned into 50 by 50 meters bins*

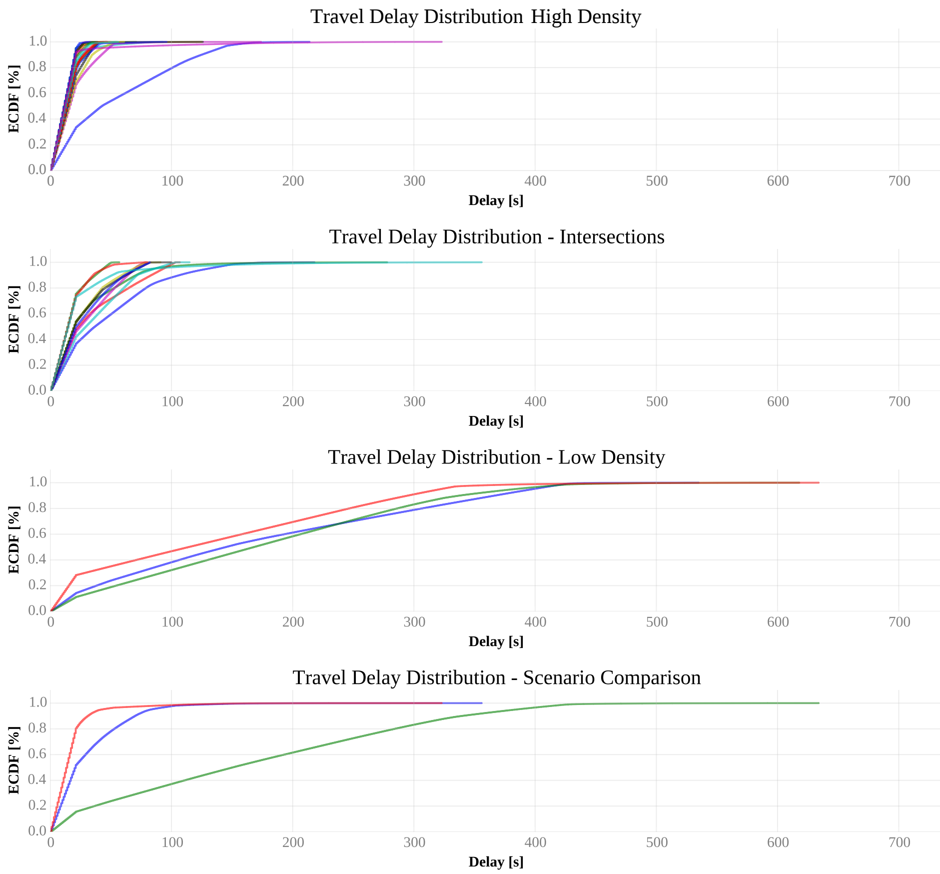


*Figure 3.6: Delay distribution due to travel time for each RSU and averaged over all RSU for each of the three scenarios.*

received, but without a harmonized view, as the freshness of the data decays as a function of the distance to a RSU. We discuss this topic further in Section 3.5.4.

### Per Road-side Unit Travel Time Delay

The plots in Figure 3.6 show the delay distributions as they are observed by the individual RSUs for each of the three scenarios. The figure shows that the per-RSU delay observed in each scenario is similar as 80% of the data is received within 20, 90 and 300 seconds for the three scenarios, respectively. Only when the distance between RSUs increases from 3 kilometers (intersections) to 10 kilometers (low density), there is a noticeable impact on the delay. Generally, the numbers fit relatively well with an average speed of 100 kilometers per hour, as was defined before.

### Comparing Delay Distribution to Cellular

Figure 3.7 shows the results for the three RSU distributions, compared to the cellular delay distribution. The cellular delay distribution is sourced from [38], in which it is described that the delay comes from bundling of multiple probes before sending them to a central server. Although the delays in the two systems have different causes, the results indicate that the performance of the RSU infrastructure is comparable with cellar collection at medium densities. Also, given a high penetration rate of vehicles, the delay could be further decreased if Vehicle-to-Vehicle (V2V) communication is used for forwarding the messages using other vehicles, this topic is investigated in Chapter 6.

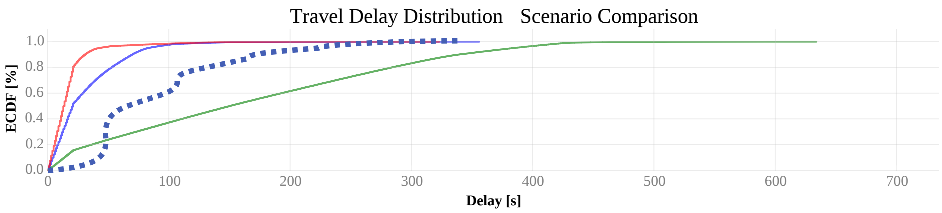


*Figure 3.7: Delay Distribution – Comparison between RSU and cellular based PVD reporting*

### Summary

The results presented until now show that a key challenge in collecting PVD via a distributed, RSU-based infrastructure is the variability in the travel-time delay depending on where the probes have been generated and the position of the RSUs. This results in that the actuality of a received message, depends on where it has been generated, as probes generated near the delay contain more recent information than probes generated far away. As a consequence, a road operator needs to anticipate a certain delay, if they wish to know the status of their entire road infrastructure. The criticality of the delay depends fully on the application that the collected probes are used for, therefore, before discussing the applicability of periodical PVD for specific applications, we evaluate how different penetration and sampling rate and travel distances impacts the accuracy of an estimated parameter.

## 3.5 Probe Vehicle Data Aggregation

For the aggregation evaluation, we consider a use-case in which we want to record the development of the average speed over time over specific segments of the road infrastructure. Therefore, we split up the full road infrastructure into sub-segments, each having the length $d$ and define a time interval $t_\delta$. For any segment and time-window, defined as $[t_{\delta-1}, t_\delta)$, we want to know how well the evaluated PVD aggregation algorithm can estimate the speed, $\hat{s}$ compared to the ground truth, $s$, when the following three parameters are varied:

- The penetration rate of vehicles equipped with OBUs.
- The sampling rate of the these vehicles with OBUs.
- The distance from the road segment to a RSU.

To simplify the evaluation, we select one specific road segment, defined as our Area of Interest (AOI), which is located within the area where a congestion occurs. This is because the algorithms should experience some variability in the input data, rather than estimating free flow traffic. This approach allows us to both determine the impact of the three parameters defined above, and to evaluate whether an increased sampling rate can be used to compensate for low OBU penetration rates when estimating the speed at the AOI. The latter is motivated by the assumption that the percentage of vehicles equipped with OBUs can be anticipated to be low initially, during the deployment phase.

The next section, Section 3.5.1, presents the three considered aggregation algorithms. This is followed by the RSU density scenarios description and pre-evaluation used specifically for this this evaluation in Section 3.5.2. Finally, the results are presented in Section 3.5.3.

### 3.5.1 Aggregation Algorithms

For this evaluation, we consider the following three PVD aggregation algorithms that use averaging to determine the speed within the AOI:

- Interval window – Interval window aggregates all probes that have been received since the beginning of the interval at a specific interval, i.e., every 60 seconds. Using this approach we would expect that for large distances between the RSU the accuracy would decline as the aggregated output may no longer reflect the actual situation due to the delivery delay. For low penetration rate it is even possible that no data has been received at all.
- $k$-newest messages – $k$-newest messages uses the $k$ most recently received messages at the point of aggregation at the specified interval. Using a constant number of samples improves on the situation where no samples were received but the information will be historically biased, as data from previous intervals is used. If $k$ is too high there is an increased probability of including information that can be outdated while a too small $k$ value risks to ignore too many samples, e.g., if more than $k$ samples have been received within the last window.

- aBox – This algorithm uses, in contrast to the previous two, the generation time of the probes to decide which probes to average over, i.e, to which interval they belong. The aggregation is triggered by a time-out when the algorithm is confident that the majority of probes have been received. To know when to trigger a time-out, the algorithm maintains an array that maps specific geographical location with the historically observed delays for that specific area, allowing the algorithms to dynamically adapt the time-out when the delay changes. While this approach can potentially include additional samples, if there are any. for each interval, the estimate for a specific geographical location and for a specific time interval depends on current travel-time.

All three algorithms take the parameters $d$ and $t_\Delta$ as input, which as mentioned define the spatial resolution and time resolution. $k$-newest additionally takes the parameter $k$, defining the number of samples that should be included in each estimate.

While the three aggregation algorithms appear somewhat similar, each has a key difference. First of all, $k$-newest and interval window operate on probes accordingly to when they have been *received* at the RSU, while aBox uses the *generation* time stamp. Using the received time stamp impacts the estimation negatively as the travel time increases while using the *generation* time-stamp requires that the aggregation is delayed by at least the duration of the travel time. A second characteristic is w.r.t. the amount of data that is generated. I.e., aBox can only provide an estimate if data has been generated within a) the given time window and b) the given AOI. Interval window can only provide an estimate if data has been *received* from the AOI within the last interval. $k$-newest depends only on the AOI requirement.

### 3.5.2 Aggregation Specific Parameters

The three aggregation algorithms are evaluated using the scenario defined is Section 3.3, but with four different RSU topologies, as illustrated in Figure 3.8. The RSU topologies are selected such that the travel distance between the AOI and the RSU that the vehicle will pass after driving through the AOI is increased. The four RSUs, one in each scenario, are located at 0, 1, 3 and 6.5 kilometers in the downstream vehicle traffic direction of the congestion. The scenario with a RSU at 0 kilometers is used as a reference scenario, defining the ideal case, as it allows the vehicles to directly upload their probes.

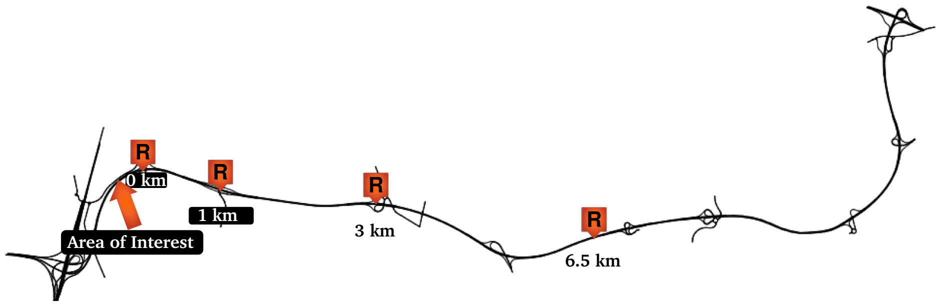


*Figure 3.8: AOI and the four RSUs. Only one of the RSUs is active in each simulation.*

To achieve a variable penetration and sampling rates, we run one simulation for each of the four RSU topologies where all vehicles sample at a pre-defined interval of one second and select a subset of the generated data in each repetition. That is, for each repetition we randomly select a set of vehicles and a subset, using a randomized offset, of their generated probes, corresponding to the current penetration and sampling rate. The varied parameters, configuration of each algorithm and the number of repetitions are listed in Table 3.4.

| **Parameter:** | **Value(s):** |
|---|---|
| **Simulation configuration** | |
| RSU distance: | [ 0 \| 1 \| 3 \| 6.5 ] kilometres |
| Warm-up duration | 10 minutes |
| Evaluation duration | 40 minutes |
| **Sub samples** | |
| OBU penetration rates: | [ 5 \| 10 \| 20 \| 30 \| 40 \| 50 \| 100 ] % |
| Sampling rates: | [ 1 \| 1/5 \| 1/10 \| 1/15 \| 1/30 ] Hz |
| Repetitions: | 100 |
| **Algorithm – All** | |
| $d$ | 40 meters |
| $t_\delta$ | 60 Seconds |
| **Algorithm – $k$-newest** | |
| $k$ values | [5 \| 10 \| 20 \| 50 \| 100 ] |

*Table 3.4: Simulation configuration.*

### 3.5.3 Results

The results presented here show how the three aggregation algorithms behave as a function of the three parameters that are varied, sampling rate, penetration rate and the distance between the AOI and the nearest RSU. For the $k$-newest algorithm, we also evaluate different $k$-values. Each approach is evaluated w.r.t. to a free-flow traffic normalized Mean Square Error (MSE) of the estimated average speed, compared to the ground truth average speed over the same area and time interval. The estimated speed is calculated by the algorithms and the ground truth is based on the raw mobility data that was generated by the mobility simulation. That is the ground truth average speed includes all vehicles that drove through the AOI and all samples they generated within the given area and time interval. In comparison, the algorithms are fed with a subset of this data, limited by whether it was delivered to a RSU and depending on the penetration rate, sampling rate. The normalized MSE is calculated as:

$$MSE = \frac{1}{n}\sum_{i=w}^{n}(\hat{Y}_i - Y_i)^2 \tag{3.2}$$

where $Y_i$ is the ground truth average speed at the $i$th time interval. $\hat{Y}_i$ is either the estimate for the corresponding time interval or, if the algorithm did not produce an estimate due to lack of data, $\hat{Y}_i$ is set to $s_q$, where $s_q$ defines the nominal speed that is allowed at the AOI. The errors are averaged over the considered time intervals, excluding the warm-up period, $w$, until the last time interval $n$, which stops when the cool-down period starts. The normalization of the estimated average speed, $\hat{Y}$, with the nominal speed, $s_q$ is done because we wish to evaluate how well the algorithms detect *deviation* from the allowed speed, primarily due to congestion. I.e., $(\hat{Y}_i - Y_i)^2$ reduces to $(s_q - Y_i)^2$, when no data is received for the given time interval.

Each parameter combination (OBU penetration rate, sampling rate, and, if used, $k$-value) is repeated 100 times, by drawing random OBUs and corresponding samples and calculating the MSE based on the extracted data. The 95% confidence interval is calculated over all repetitions and combinations that are considered, which depends on the parameters which is varied. I.e., a single data point in the penetration rate evaluation consist of $5 \times 4 \times 100 = 2000$ MSE measurements while for the sampling rate we include $7 \times 4 \times 100 = 2800$ MSE measurements.

The results presented here are heavily scenario specific; the traffic situation, the size of the AOI and the time window that is considered all have an impact on the results. I.e., as we use an AOI that spans a 40 meters road segment, the probability of a vehicle even generating a probe within the considered area depends on the speed of the vehicle and its sampling rate. Therefore, we do not focus on how well an algorithm performs but rather how they react when we modify a specific variable.

### Travel Time Delay

Before presenting the estimation results, we quantify how the delay distribution behaves for the specific AOI for which we are estimating the speed. Figure 3.9 shows the delay (y-axis) of a probe generated at a given time (x-axis) over the considered simulation scenario for the four RSU scenarios. The distribution of the variation is shown in Figure 3.10, normalized w.r.t. the minimum delay.

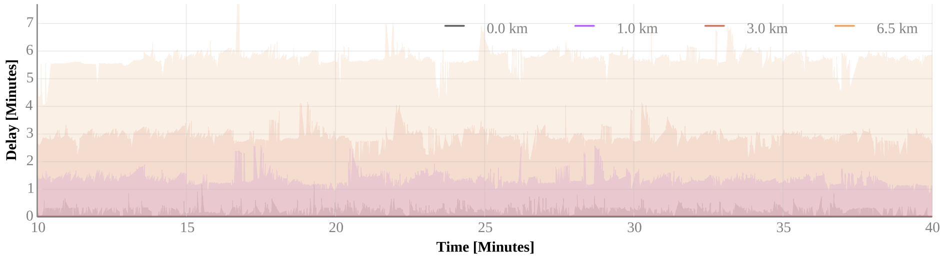


*Figure 3.9: Delay between generation and delivery of probes as a function of time.*

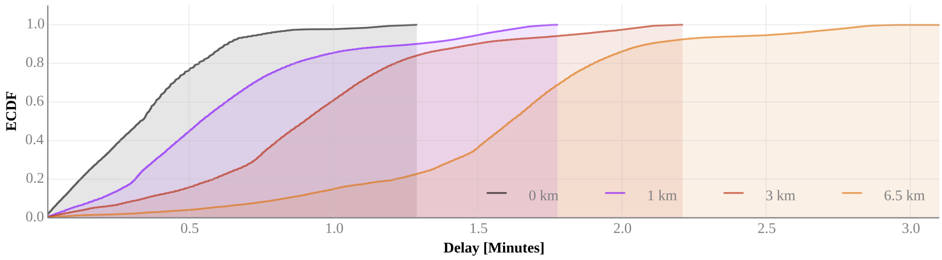


*Figure 3.10: Delay distribution, normalized w.r.t. minimum delay.*

Here we see that, while there is a relation between distance and the delay, the delay varies over time, depending on e.g., the traffic situation and driver attitude. The results in Figure 3.9 shows that a delay of on average around 0.3, 1.5, 2.8 and 5.5 minutes can be expected for each of the four RSU scenarios, respectively. According to Figure 3.10, the estimate can be based on probes that are even older.

### Estimation Error as a Function of Penetration Rate

The penetration rate defines how many vehicles of the full population can generate samples, which, together with the sampling rate, drives the probability that a vehicle generates a probe within the AOI. Figure 3.11 shows how the MSE changes as a function of the penetration rate when averaging over all travel distances and sampling rates. At low penetration rates, both aBox and interval window are impacted by the lack of data within the considered time windows. The accuracy of both increases as a function of the penetration rate, but it increases faster for the aBox approach for two reasons. Due to buffering used in aBox the probability of reviving additional samples increases and, mainly due to the synchronization, as is further discussed when evaluating how travel distance impacts the estimation error below. $k$-newest on the other side provides slightly better results at low penetration rates, but these do not improve significantly as penetration rate increases, due to the static $k$ value.

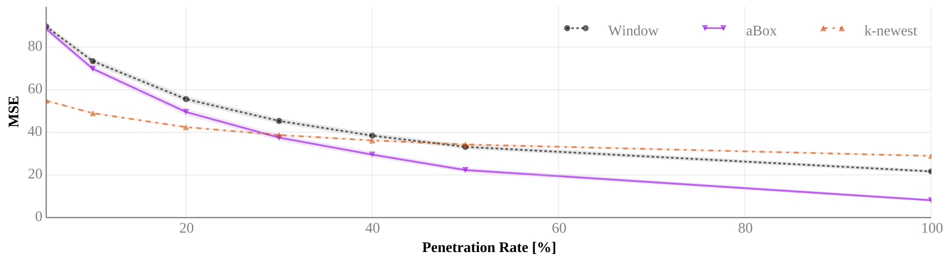


*Figure 3.11: Mean square error as a function of penetration rate for the three aggregation algorithms, from 5% to 100% penetration*

### Estimation Error as a Function of Sampling Rate

The estimation error for the sampling rate, shown in Figure 3.12, follows a similar trend as was observed for the penetration rate, except that the error reduces slightly faster as the penetration rate is increased. This is due to the increased probability of a vehicle capable of generating PVD actually generating a probe within the AOI. When evaluating the estimation error for the highest sampling rate, 1 Hz, see Figure 3.13, we observe that the estimation error is minimized for each algorithm already at a penetration rate of 20%, indicating that, when necessary, the sampling rate can be used to compensate for a lower penetration rate.

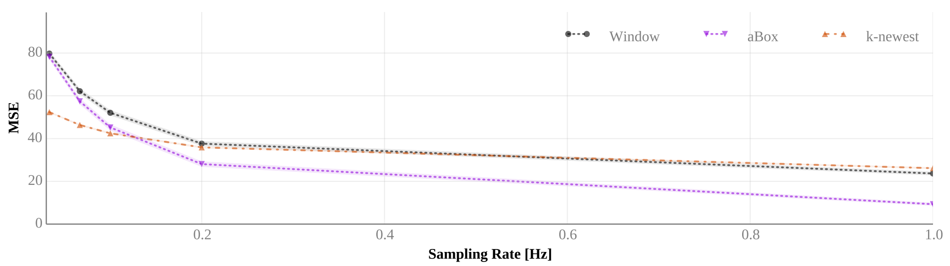


*Figure 3.12: Mean square error as a function of sampling rate for the three aggregation algorithms.*

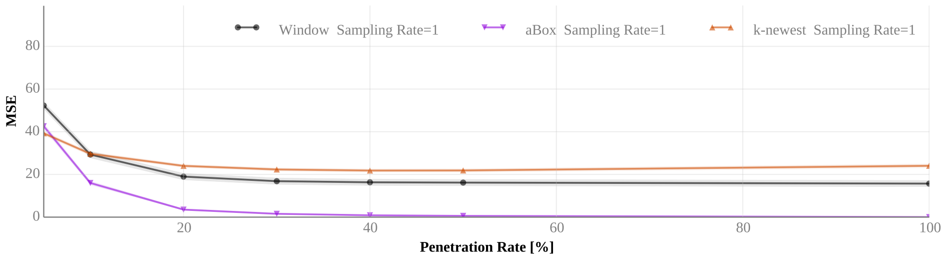


*Figure 3.13: Mean square error as a function of penetration rate for the three aggregation algorithms using a sampling rate of* 1 *Hz.*

### Estimation Error As a Function of Distance

The travel distance impacts, together with the traffic situation and the driver, the delay from when the data is generated until it can be delivered and processed. Unsurprisingly, aBox is not impacted by the delay, as illustrated in Figure 3.14, as its designed to take it into account when aggregating the collected probes. Interval window can only match the performance when the data is received immediately, i.e., when the RSU is near by the AOI, but the estimation accuracy deteriorates when the travel distance increases as the delay between an event occurring and until its is detected increases.

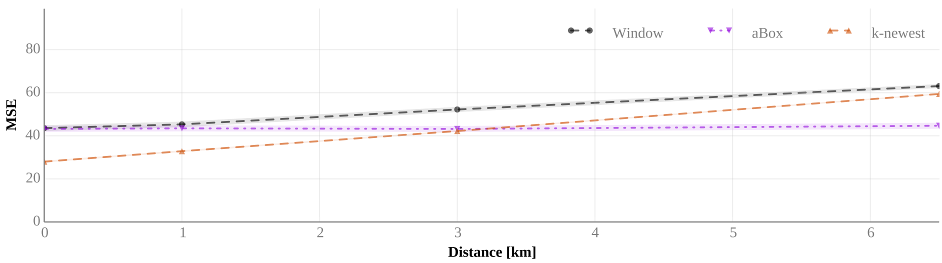


*Figure 3.14: Mean square error as a function of travel distance for the three aggregation algorithms.*

## 3.5.4 Discussion

We have observed that neither of the three aggregation algorithms alone provides an optimal solution, and a trade-off between accuracy and delay has to be made. Here we discuss the applicability of the aggregation algorithms using different application scenarios with different purposes and requirements; traffic estimation, event detection and general sensor data collection.

As discussed in Section 3.4, the collection delay of PVD due to travel time depends on the combination of distance, traffic situation and driver attitude. In particular, drivers driving above the speed limit, would, if traffic conditions allow it, arrive earlier while slower drivers would arrive latter. The application that the probe data is used for, also has an impact on the requirements. For travel time estimation, it can be reasoned that if a fast moving vehicle is capable of arriving early at the RSU that the road is relatively clear, thus only a subset of probes are necessary. Average speed, however, requires a more representative sample set from all the vehicles, as probes arriving early would not be representative of the actual average speed. The same applies for most applications that rely on non-traffic related PVD.

Most traffic estimation scenarios require timely information rather than high accuracy to be useful. E.g., for *management* applications, the exact position of a congestion is less important as long as vehicles can be informed about an alternative route before arriving at the congested area. Rather, the travel time is of interest as it provides information about the consequence of following a certain route. When a fast moving vehicle is capable of delivering its data, then the path should be clear. This however, requires other mechanisms, which are capable of distinguishing between whether the PVD provider is a truck or personal vehicle. For historical data, used to determine general trends, an approach similar to aBox is suitable, as accuracy is more important. The time-out can also be increased such that all samples are taken into account.

Generally, traffic related *events*, like congestion or slippery roads, should be detected by the vehicle, and reported using event PVD. The results show that at low OBU penetration rates, the probability of a vehicle generating a sample at a small AOI is low. Rather, the vehicle should generate a detailed report when detecting the event and, if the event type is of high importance use any means possible to deliver it to the TCC; using other vehicles as forwarder or alternative communication technologies. As multiple vehicles detect the event, the confidence can be improved and movement of the event can be monitored.

Interval based PVD is mostly relevant for detailed and accurate sampling of specific areas. For example increasing the monitoring on roads surrounding a congestion to track the traffic pressure, evaluating g-force impact on the driver when driving through a sharp curves at different speed to identify safe speed regulation or collecting general information about and around the road infrastructure.

## 3.6 Conclusion

In this chapter we used realistic vehicular mobility simulation and simplified wireless network simulation to identify characteristics of PVD collection when using an 802.11p based RSU infrastructure. As in most environments that are based on sensor data collection and processing, a key limitation that was confirmed is variability in the delay between when a sensor measurement, or probe, is generated and until it has been collected and processed. In the vehicular environment, however, there is usually a correlation between when the information is of most relevance and an *increase* in the delay: vehicles that arrive at a congestion have to travel through the congestion before they can deliver the information they have collected, if there is no RSU in their vicinity.

A key take away message from this chapter is that applications that depend on PVD as input should make use of all their options available. While the main focus here is on periodically generated PVD, a significant advantage can be achieved by using a combination of event PVD and periodic PVD. Traffic state estimation can in particular benefit from using e.g., event based information, which can be significantly more compact and detailed for specific events thus easier to manage the collection of, to rapidly gather high-level information and disseminate it to the relevant used. At the same time, periodically generated PVD can be used gather detailed information that be used for predicting how the traffic state will evolve. The same is the case for non-traffic state information applications that would collect PVD from the environment. However, as the amount of data that is collected from certain regions at a certain time can be unpredictable, as it depends on the number of vehicles capable of collecting sensor data opportunistically passing through, a certain amount of control and management of what, where and when vehicles should collect is needed to make sure that the amount of data collection is evenly distributed. This allows each application to specifically state their needs and increase the flexibility such that these needs can be fulfilled.

# Chapter 4

# Controlled Probing – Concept and Design

In this chapter we define how the management of Probe Vehicle Data (PVD) can be realized in the context of a distributed infrastructure of Road-side Units (RSUs) by using standardized message formats. This approach is necessary, as it is anticipated that the amount of data generated by vehicles either exceeds the available resources, or is too costly to realize. As application requirements vary significantly from application to application, we focus here on identifying potential limitations of managing PVD in the considered system architecture, and use this chapter to motivate the following two chapters, Chapter 5 and Chapter 6, by identifying two limitations w.r.t communication when using the considered infrastructure.

## 4.1 Introduction

A large range of applications and services are expected to be enabled by sensor data collected throughout the road infrastructure. These include both traffic optimization applications where the sensor data is used to identify congestions, travel time, etc., and general applications that monitor the environment for pollution, weather services, etc. The range of applications is limited by the available sensors in the vehicles, that are accessible by the On-Board Unit (OBU), and the communication and storage resources needed to realize the collection of the sensor output. Application requirements generally differ w.r.t. what type of sensor data is needed, the spatial/time resolution of the data, their accuracy and when and from where the information is needed, depending on purpose of the application. For example, monitoring of temperature is needed during near-zero temperatures to predict and detect potential hazardous situations such as slippery roads due to an increased risk of black ice but obviously this information is of less relevance during hot summer nights. Dynamic management of the sensor data collection is therefore necessary to prioritize sensor data collection based on what is needed, thereby possibly enabling a larger range of applications even when resources are constrained.

The probe data eco-system consists of three main actors; the vehicles, that are generating the probes needed to realize the applications, the applications, that utilize the collected

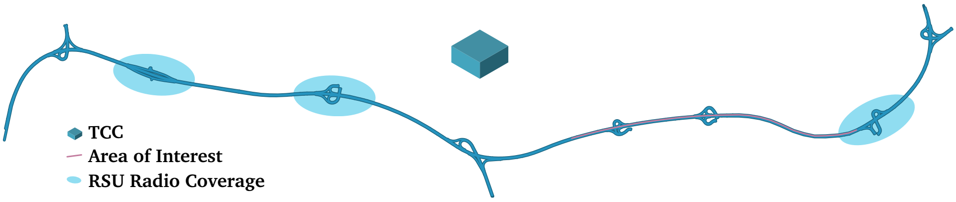


*Figure 4.1: PVD system architecture. Vehicles produce probe data, the TCC process the data and provide it to the consumer. The communication of probe data is facilitated by the RSU infrastructure.*

data, and the end user of the extracted information, i.e., the consumer that benefits from the information. In most traffic applications, the drivers are one of the main consumers of the processed data, as they benefit from the overall increase in information that is relevant for them. In addition, the system also includes the RSUs, which are used to facilitate the information exchange between vehicles and the probe data applications. RSUs provide an 802.11p wireless communication interface that enable them to interact with passing vehicles and a communication link, typically wired, that connects them to the application provider.

## 4.2 Background Information, Problem Formulation and Statement

Typically, in PVD generation, each vehicle periodically samples one or more sensors using a predefined or preconfigured value, and combines the result with relevant context. This context usually includes the location, time and sensor value accuracy of when and where the probe was created. This message format is formalized and standardized by ISO in [39]. Management of sensor data collection within the context of vehicular sensor data has been formalized in [40]. This standard defines messages, so called Probe Data Reporting Management (PDRM), which can be used to inform vehicles of exactly what information they should collect. The key purpose of these management messages is to inform the vehicle of:

- *Where* to generate probes – Depending on application type, information from selected areas of the road infrastructure are needed.
- *What* type of probes to generate – This covers the types of sensor information that is relevant for the application, speed, temperature, humidity, etc.
- *When* to generate probes – Some applications have specific requirements regarding when, time of day, week, ect., when they need sensor information, and switching on or off the collection depending on the current quality.

- *How* to generate probes – Refers to the sampling interval and how often a probe should be generated. E.g., every 100 meters, 30 seconds, over/under a specific threshold, etc.

While [40] defines a *message format* for PVD management, it does not define, nor investigate the challenges, how management of PVD can be realized in the context of a spatially distributed infrastructure of access points, where short-term connectivity is dominant, or how the exchange of information can be realized.

### 4.2.1 Problem Formulation, Statement and Contribution

Collection and management of the collection of PVD depends on two parts. First of all, vehicles needed to be informed about what, where and how to collect. Second, the communication, i.e., the exchange of management messages and PVD, needs to be facilitated as efficiently as possible.

Key characteristics of the architecture that is considered here, illustrated in Figure 4.1, is the geographic location of the RSUs and their distribution. For the *collection* of PVD, this means that we can expect that the delay between when the vehicle generates a probe and until the probe is delivered can vary depending on the RSU density, the traffic situation and driver attitude, as discussed in Chapter 3. Dissemination of PDRMs is restricted by the exact locations of the RSUs, as vehicles need receive information about when, what and where to collect probes.

Another challenge, as discussed in Chapter 2, is the exchange of information between the vehicle and the RSU, as the communication varies depending on the current position of the vehicle and the static RSU.

The problem statement driving this chapter is motived by the fact that there is a need to be able to manage the generation of PVD in order to be able to enable a wide range of applications. While message formats have been defined that achieve this, they are not directly applicable to the distributed RSU infrastructure and need additional work. To overcome this limitation, we define a framework that improves the challenges for PVD collection and management in an RSU based infrastructure.

The contribution is a follows:

- We describe the steps needed to realize management of probe data in the context of a distributed RSU infrastructure.

### 4.2.2 Terminology

We define the following terminology:

- *Application* – Defines the information sink. I.e., where either the raw or processed PVD is destined to.
- *Task* – Define a specific data collection task that the application needs to fulfill its purpose. It consists of the configuration of what, where, when and how to collect probes.
- *Area of Interest* – Defines the area where data needs to be collected from to fulfill the task, i.e., a delimited geographical area, a road segment, etc.
- *Upstream RSUs* – Upstream RSUs are located *ahead* of the Area of Interest (AOI), i.e., a vehicle would pass these RSUs before driving through the AOI, thus they can be used to provide information *to* the vehicles about the upcoming AOI.
- *Downstream RSUs* – These are the RSUs the vehicles can pass by *after* driving through the AOI, and can be used to collect data *from* the vehicles.

### 4.2.3 Example Use-Cases

**Special Events** – Imagine that there is some special event; a football game, road works or similar type of event which has impact on the traffic flow in a given area. As these events are scheduled in advance and are known to cause congestion, a road operator can configure the system to collect quantitative data of what is going on; namely configure various tasks at key points around the event, and thereby be able to know if and where problems are developing. The surrounding road infrastructure is of particular interest, such that the operator can identify the best alternatives and inform drivers how to avoid bottlenecks. Here, Controlled Probing allows road operators to be pro-active and improve the situation as they evolve.

**Scheduling of Large Scale Data Collection** – Vehicular traffic is constantly evolving over the course of the day, weekday etc., and thus needs more or less constant level of monitoring. Non-traffic related events can have different monitoring needs. Here we consider a use-case in which someone is interested in getting statistically sound samples of a particular type for a specific area. As an example, we assume that a cellular operator wants to gather reliable information how the installation of a new base station impacts the network quality. The operator is interested in an evenly distributed number of samples, but the traffic density varies significantly over the roads that are serviced by the new base station, resulting in an uneven number of samples.

Controlled Probing provides the option of being able to schedule exactly when and where to collect, and algorithms can be applied which only collect data from a subset of the area of interest at a time in order to reduce the strain on the infrastructure, and finally completely shut down the measurement campaign when all data has been collected.

## 4.3 Controlled Probing – General Concept

Controlled Probing enables applications to define various tasks consisting of what, where and when probing should be executed. This consists of disseminating the management message to the appropriate vehicles, i.e., the vehicles that are expected to drive through the AOI. As the probes are received, Controlled Probing aggregates the messages for processing, either locally, at the RSU, or centrally, at e.g., the TCC, before handing them over to the application. When applied to the RSU infrastructure, this entire process consist of seven steps, as illustrated in Figure 4.2 and detailed below.

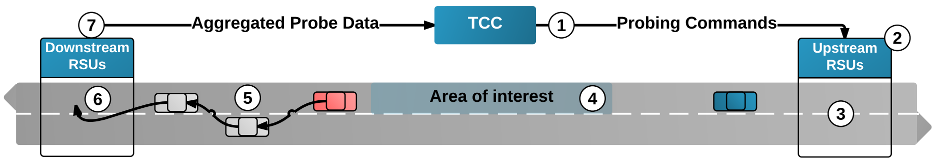


*Figure 4.2: High level overview of Controlled Probing, showing the main steps being executed during the lifetime of a task. See text for detailed description.*

1. The received task is formulated as a Controlled Probing task and disseminated to RSUs that are located upstream of the AOI. This is done by searching the road infrastructure against the driving direction, following a path until a RSU is found, reducing the problem to searching a graph, where roads are edges tagged with whether they are occupied by a RSU and intersections are vertices.[1]

2. The identified RSUs broadcast tasks periodically over the wireless interface, such that all vehicles passing by are informed of the task ahead. The repetition rate depends on the contact duration between the RSU and the vehicles, and should be a trade-off between resource consumption and achieving a high percentage of informed vehicles. How this can be achieved is analyzed in Chapter 5.

3. Vehicles passing any of the upstream RSUs receive the broadcasted tasks and determine which are relevant for them, judged by if they will drive through the AOI, if they can comply with the requirements, etc.

4. When the vehicle detects that it has entered the AOI it starts to generate probes accordingly to the task definition.

5. When the vehicle has finished the task, it can decide the following:

   - Store the probes until a communication opportunity arrives, i.e, it encounters a RSU.

[1] Alternatively, if no upstream RSUs are found, or one or more entry roads are uncovered, the algorithm can select the nearest RSU to the AOI instead and use multi-hop to forward the message upstream of the AOI.

- Use other vehicles to forward the probes to a RSU using multi-hop. This choice depends on the importance of the specific task. Using multi-hop is evaluated in Chapter 6.

6. The delivery of the generated probe data from the vehicle to the RSU, either by the vehicle that generated the data or as the last hop if multi-hop is used, should be done as efficiently as possible. We investigate last hop communication performance in Chapter 5.
7. The PVD can arrive at different RSUs, and must be forwarded to one specific RSU for processing or aggregation or forwarded directly to the TCC, which can then provide the data to the application.

As mentioned, the improvement that can be expected by using Controlled Probing is highly application dependent, therefore, we focus on evaluating and improving the above mentioned communication challenges in the following chapters.

# Chapter 5

# Reducing Communication Costs Through Performance Maps

In this chapter we evaluate how the information exchange between Road-side Units (RSUs) and vehicles can be improved by using context information about the communication properties of an individual RSU. The problem is motivated by observed Frame Success Ratio (FSR) at different distance from the RSU and we propose to use a mapping between a performance metric and a geographic location, a so-called performance map, for the scheduling of communication. Specifically, we consider the use-case of dissemination of management messages and collection relevant for the Controlled Probing approach presented in Chapter 4.

The content of this chapter is based on a modified version of [2], where we have included the considered performance maps can be used to improve dissemination of broadcast messages. Section 5.4.1 has been included unmodified in its entirety for completes, and is originally authored by Stefan Rührup.

## 5.1 Introduction

Infrastructure-to-Vehicle (I2V) and Vehicle-to-Infrastructure (V2I) communications using RSUs as points of information exchange is envisioned to improve traffic efficiency through the exchange of information between drivers and road operators. While road operators offer up-to-date information about traffic status, warnings and route recommendations, each vehicle potentially offers a piece of information that helps to obtain an accurate picture of the traffic situation. In the context of Controlled Probing the vehicles must also receive management messages, informing them what and where to collect. The communications capacity of each RSU is shared between the two information flows while leaving room for high priority safety communication between the vehicles on the same channel.

Information dissemination in I2V is usually relevant for most vehicles passing by an event or incident location. For this reason is is usually disseminated to the vehicles through broadcasts communication. The amount of information each RSU has to disseminate depends on the amount of upcoming events, the RSU density and the area that the individual RSU is responsible for. Information is disseminated in self-contained messages, such as Decentralized Environment Notification Message (DENM)[41] for safety information, Signal Phase and Timing (SPAT)[42] for optimizing traffic around light-regulated intersections or Probe Data Reporting Management (PDRM) for Controlled Probing.

Vehicles are able to periodically sample their own speed, acceleration, but also road temperature etc. This data is known as Probe Vehicle Data (PVD) and can be reported to the road operator via V2I communication, wherever a RSU is within reach. In this chapter, we assume that PVD is a data element containing a fixed number of sample locations and encapsulated in a dedicated PVD packet, and small enough that it can be sent to the RSU in a single transmission. This message is transmitted to a RSU when a vehicle is passing by.

In order to let vehicles know that a RSU is present, the RSUs broadcast periodic messages, triggering the vehicle to send a PVD packet to the RSU. As an example, in Wireless Access in Wireless Environments (WAVE) [43] the reception of one or more beacons (service advertisements), depending on configuration, triggers a channel switch to the Service Channel (SCH), where non-safety communication can be exchanged. This can be an opportunity for the vehicle to deliver any queued PVD packets. In ITS-G5 [44], the GeoNetworking layer allows the nodes to specify their type, i.e., that they are a RSU. Similar to WAVE announcements, a beacon can be generated that has a minimum, configurable, broadcast frequency.

### 5.1.1 Problem Formulation and Statement

We distinguish the two types of information exchange between the RSU and the vehicles by their categorization: PVD messages have a one-to-one relationship where each vehicles has to deliver its content to the RSU while disseminated information, i.e., PVD management messages, have a one-to-many relationship, where the management message must be disseminated to as many vehicles as possible.

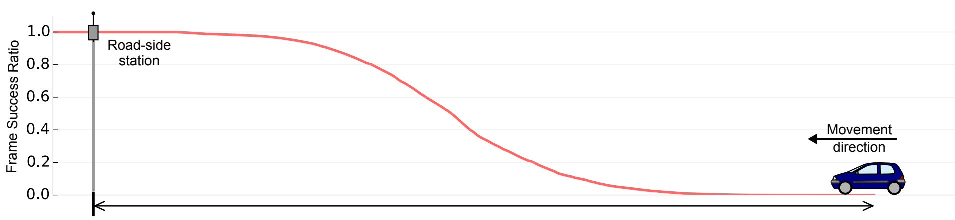


*Figure 5.1: Drive-by scenario: A vehicle is approaching an RSU. The FSR determines areas of reliable communication. It is here determined by a simple path loss and fading model.*

The information disseminated by the RSU may cover a significant geographical region in either traffic direction. While each individual message is self-contained, typically one message[1] per upcoming event, whether it is a hazardous event, rerouteing information or PVD management message, is required. In order to make it feasible to disseminate large variety of information and to avoid unnecessary interference with safety communication, i.e., Cooperative Awareness Messages (CAMs), it is required that the information dissemination resource consumption is minimized. As the majority of I2V information dissemination is done in broadcast mode, the challenge is to identify the minimum repetition such that the majority of vehicles receive all messages. This repetition rate depends on the three factors:

- Radio coverage range – This parameters depends on the environment of the individual RSU, its surroundings, antenna type, configuration, etc.
- FSR over the radio coverage range – Normally, the performance varies both as a function of distance, but also depending on the environment. Figure 5.1 shows an example of this, when using a simple path loss and fading model.
- Vehicle speed – The vehicle speed determines the duration of how long the vehicle is within radio coverage. Usually, the speed will fluctuate depending on the traffic situation, vehicle type, etc.

The message exchange *from* the vehicles to the RSU is inefficient if performed at a non-optimal location, where the FSR is low. Usually, the FSR decreases as the transmitter-receiver distance grows (see Figure 5.1). The RSU broadcasts its beacons periodically, and repetitions increase the chance of reaching a vehicle in non-optimal locations, even more so, if *any* message from the RSU can be used as a trigger. If the vehicle reacts immediately and transmits its PVD packets, while still being in a non-optimal location, the chance is low to be successful. In this case, the vehicle needs an unknown number of retries until success, as exemplified in Figure 5.2. While the beacons of the RSU reach all vehicles and periodic retransmissions are desired, it is not desired that each vehicle transmits PVD packets too many times, resulting in unnecessary channel load.

Given a vehicle passing by an RSU, which periodically requests PVD from the vehicle, where and when (and how often) does the vehicle have to transmit its PVD messages in order to minimize communication cost and maximize reception (by the RSU ) success.

### 5.1.2 Contributions and Outline

The methodology used in this chapter is based on an analytical approach, showing the feasibility of using contextual information about a RSU's communication performance

[1] A DENM is in the range of 200-300 bytes, depending on type.

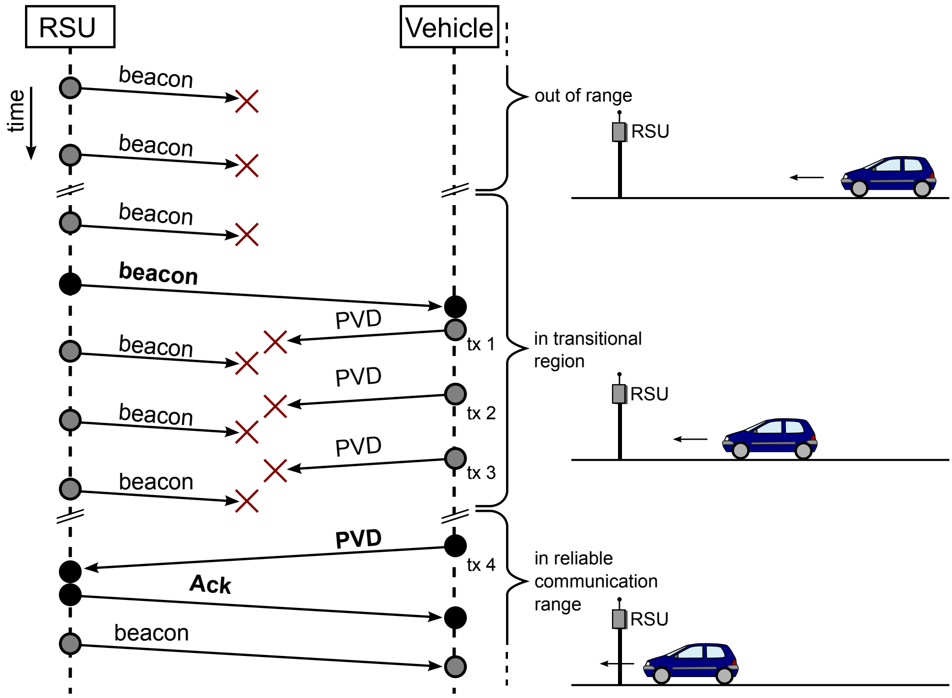


*Figure 5.2: Message sequence of an approaching vehicle. With progressing time (top to bottom) the vehicle approaches the RSU. After receiving the first beacon, the vehicle transmits the PVD packet several times without success before reaching the RSU (PVD transmission number four) and receiving an acknowledgment.*

over a geographical region, a so called performance map, and to indicate the potential benefits. The lessons learned are then used to define the methodology for defining and applying performance maps. Specific contributions of this chapter are:

- We analyze delivery probabilities using both simulation and field measurements to identify I2V broadcasting, see Section 5.2
- We investigate basic strategies to deliver PVD, including broadcast and unicast strategies. These strategies are evaluated w.r.t. delivery success and number of messages used. See Section 5.3.
- We show a methodology for determining the optimal point for V2I communication, from vehicle to RSU, based on statistic of vehicles' transmissions and location and that the distribution of delivery performance around the RSU can be qualitatively represented in a map with constant overhead, see Section 5.4.1.
- We provide a methodology that estimates the necessary number of retransmission attempts needed for the vehicle to deliver PVD messages to the RSU with a high proba-

bility, see Section 5.4.1.

### 5.1.3 Related Work

The communication profile of IEEE 802.11 [45] networks in highly mobile scenarios has been measured in numerous field trials and experiments, all identifying poor communication performance at the outer perimeter of the communication range. In [46] the communication range is split into three phases, entry, production and exit, to distinguish this variation, and points out that the variation should be considered in the protocol design. In [47] and [48] the terms reliable communication range and unreliable communication range are used, identified by e.g., a FSR above 70 % and below 10 % respectively. Their results also indicate that three phases are not always enough to accurately quantify the communication profile, due to high variability within the production phase. To determine the unreliable communication range, knowledge of the actual FSR (e.g. from measurements) is assumed. We use these works as motivation for performance maps that can capture variability in the communication profile when using ad hoc communication. We also describe a method to estimate the FSR on the fly without reference measurements and with *incomplete* information.

For vehicular access using traditional 802.11 WLANs Hadaller et al.[49] showed experimentally that current protocols (802.11 MAC and TCP/IP) reach only a fraction of the maximum possible throughput, and that losses during connection setup are high. They recommend to avoid fringe areas and postpone communication until the production phase (see above) is reached. Additional relevant observations are that the measured Received Signal Strength Indication (RSSI) values were consistent over multiple measurements, similar performance results were also achieved in [47] w.r.t. FSR, making a strong case for the reliability of performance maps based on active measurements.

Specific examples of performance map variants can be found in e.g., [50], [51] and [52]. Both [50] and [52] apply performance maps, specifically bandwidth maps, for improving streaming through adaptive modulation of the stream based on the *expected* future performance while mobile, thus improving quality of service. [51] proposes using a database for predicting location-based handover between wireless and cellular networks through look-ahead. However, our considered use-case consists of data that fits in individual frames, and we assume that a vehicle operates independently of a centralized service. Therefore, we focus on providing an ad hoc suitable approach, that is in line with the use cases and applications that are expected to be realized through ITS-G5.

Message *formats* for PVD have been defined by ISO in [40] and for management of PVD in [53]. While specifying the content, theses standards do not actually define the protocol for message exchange.

## 5.2 Analysis of Beacon Reception Probability

We quantify the problem using numerical evaluation based on the following analytical model. The scenario consists of vehicles receiving and transmitting messages at different distances to the RSU, defined as $d$. Each transmission by the RSU is a random experiment with probability $x_i$ defined by the distance and a FSR function. $i$ is the index of positions at specific distances between the vehicle and the RSU, where the transmission takes place. We model the number of successful reception events, by the vehicles, by the random variable $X$. Using a FSR function extracted from simulation and field measurements, we compare the probability of receiving at least one message as a function of the distance $d$. The considered scenario is similar to the one illustrated in Figure 5.2: A RSU is periodically broadcasting beacon messages while a vehicle that has a payload to deliver is approaching.

The two models we use is the combination of the Dual Slope Log-distance and Nakagami path loss fading model and the Hidden Markov Model (HMM) based two phase Gilbert model, trained on field measurements [54]. The shaded areas in Figure 5.3 show the FSR generated by the Dual Slope and the Gilbert model, respectively. In this evaluation we only consider the entry part of the drive by, as the data generated by both models is symmetric around the RSU.

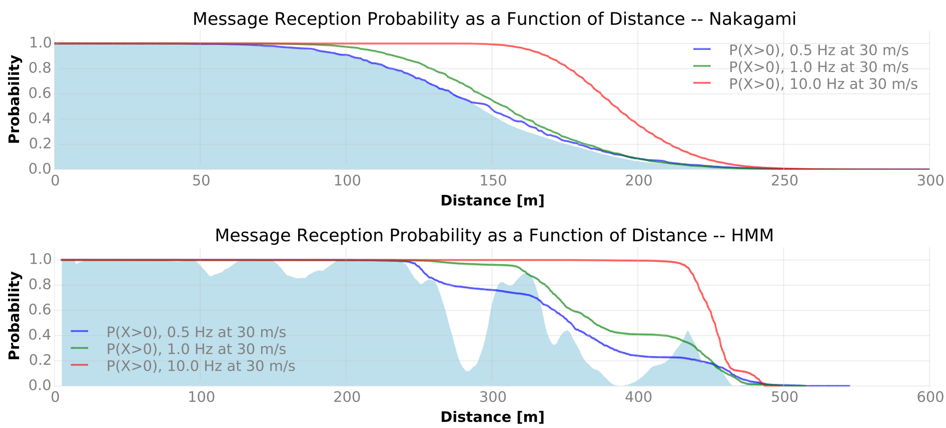


*Figure 5.3: Beacon reception probability as a function of distance, speed and FSR, using the NS-3 Nakagamin and a Gilbert model trained on field trail measurements. Shaded areas show the FSR*

Using the FSR functions, we estimate the probability of receiving at least one beacon from the RSU after $n$ beacon transmissions as:

$$P(X > 0) = 1 - P(X = 0) = 1 - \prod_{i=0}^{n}(1 - x_i) \tag{5.1}$$

where

$$x_i = FSR(d_i) \tag{5.2}$$

is a specific FSR value sampled from either of the two FSR functions at $d_i$ defined as:

$$d_i = d_{max} - i \times \frac{speed(v)}{frequency(f)} \text{ for } i = 0...n \tag{5.3}$$

$$n = floor(d_{max} \times \frac{speed(v)}{frequency(f)}) \tag{5.4}$$

To avoid synchronization between the arrival of the vehicle and the timing of a broadcast, the calculation is averaged over 200 repetitions, thus for each repetition $d_{max}$ is randomly selected as:

$$d_{max} = max(distance) + rnd(0, \frac{speed(v)}{frequency(f)}) \tag{5.5}$$

The averaged probabilities are plotted in Figure 5.3 as the function of the distance. At 1 hertz, $P(X > 0)$ approaches 1 at $d = 150$ and $d = 430$ meters for the NS-3 and the Gilbert model, respectively. The corresponding FSR value is in both cases around $0.4$. This means that the vehicle will have received a beacon from the RSU, but would in most cases need multiple retransmissions to be able to successfully respond, the vehicle reacts immediately. The second message is that even at low broadcast frequencies, the vehicle reaches a high probability of receiving the beacon from the RSU, resulting in the *repetition* of the beacon, in the case that is contains a management message or traffic information, is unnecessary. Figure 5.4 shows the reception probability $P(X > 0)$ over a full RSU pass by a vehicle, as a function of both vehicle speed and the broadcast frequency. In addition, the total number of messages sent during the passing and the normalized resource consumption cost expressed in message per second are illustrated.

The reliability cost function weights high reliability and low communication cost, where the cost is calculated in messages per second. Thus, the higher the outcome, the better the performance of the combinations of parameters.

## 5.3 Basic Strategies for PVD Delivery

The following lists and discusses the different approaches for PVD delivery that are considered in this paper, highlighting their advantages and limitations.

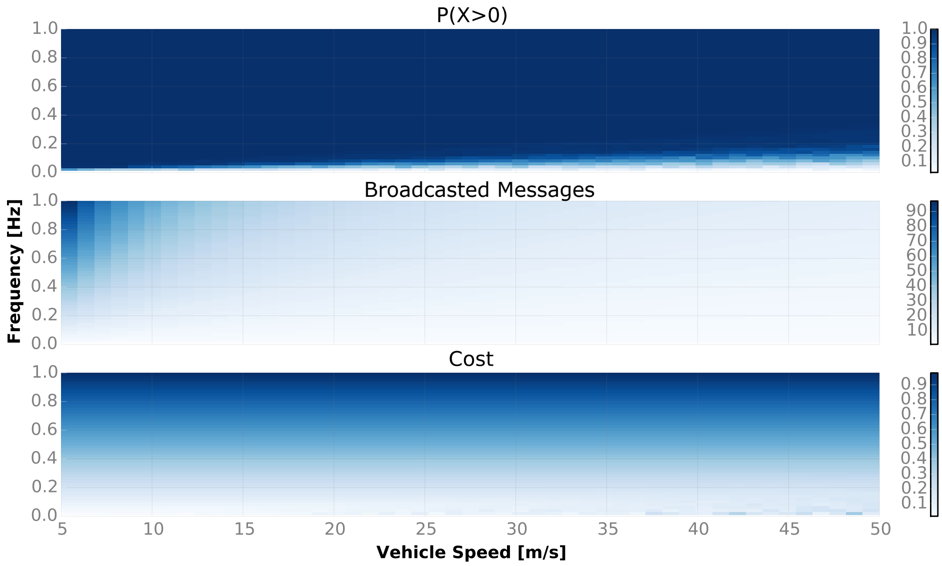


*Figure 5.4: Probability of receiving at least one beacon during a RSU passing at different broadcast frequencies and vehicle speed, the total number of messages broadcasted and the normalized cost expressed as messages per second.*

### 5.3.1 Basic Algorithms

We evaluate the following basic strategies for PVD transmission from a vehicle to the RSU. They are all triggered when the vehicle receives a beacon from the RSU, but react differently.

- **Immediate Broadcast (IB)** with a single transmission – After receiving a beacon, the vehicle immediately broadcasts its PVD packet only once. This serves as a reference scenario rather than an actual solution.
- **Delayed Broadcast (DB)** with a single transmission – After receiving the first beacon, the vehicle delays its PVD transmission until it reaches a certain distance threshold to the RSU. If the distance is already lower than the given threshold, the vehicle reacts immediately.
- **Reactive Broadcasts (RB)** with multiple transmissions – The vehicle reacts to *every* received beacon by sending its PVD packet. This approach is expected to be highly successful at the cost of generating significant communication overhead.
- **Immediate Unicast (IU)** with retries – Similar to IB, but using unicast with unlimited retries.

- **Delayed Unicast (DU)** with retries – Similar to DB, but using unicast with unlimited retries.

We include broadcast and unicast message transmission, though current ITS standards favor the broadcast mode. Unicast transmissions directly address the RSU and trigger an acknowledgment. In case of a missing acknowledgment (after timeout), the sender retransmits the same message. The number of retries is usually fixed, but even a fixed number of retries can create a burst of transmissions on the channel and increase the channel load. Broadcasts are not acknowledged. Here, a fixed number of repetitions can increase the delivery success, but it can be regarded as wasteful to repeat transmissions when the first try was successful.

### 5.3.2 Performance Metrics

The five algorithms are evaluated w.r.t the following metrics:

*Success rate*: As the scenario we are investigating consists of a single vehicle delivering a single payload, we call a vehicle's traversal of the RSU coverage area *successful* if the vehicle delivers at least one PVD packet to the RSU. The *success rate* is given by the number successful traversals over all traversals.

*Cost*: Communication cost is defined by the number of transmissions by the On-Board Unit (OBU) in each RSU traversal. It is desired to keep the cost low, because a high utilization of the communication channel comes with an increased message loss.

### 5.3.3 Simulation Scenario

The scenario consists of a single RSU, which periodically broadcasts beacons and a single vehicle that has a single PVD element to be delivered (see Figure 5.5). The beacon message indicates to the vehicle the presence of the RSU and that the PVD packet should be transmitted to the RSU. The vehicle is driving at a defined speed, ranging between 10-40 meters per second (36-144 km/h) towards the RSU. The time and location of PVD transmission(s) depends on the chosen strategy, as described above. On the lanes in the opposite direction, we assume a slowly moving traffic jam, where vehicles do not transmit PVD, but periodically broadcast safety beacons, which create channel load and interfere with PVD transmissions. Safety beacons, e.g. cooperative awareness messages (CAM) [55] or basic safety messages (BSM) [56], are suggested to be transmitted at frequencies of up to 10 Hz according to ITS standards. The traffic jam is not intended to model a certain traffic situation, but to create an element of the simulation model that can be tuned (via vehicle density) to create different levels of interference on the channel.

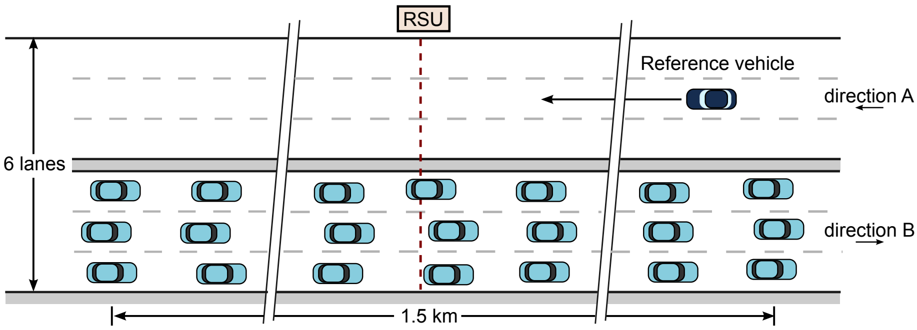


*Figure 5.5: Simulation scenario: A vehicle is approaching an RSU. Vehicles in slow moving traffic jam on the lanes in opposite direction cause interference to PVD delivery by background transmissions.*

### 5.3.4 Simulation Model

Our simulations are generated using NS-3.19[2]. The simulations are used to evaluate how the PVD delivery strategies perform under various vehicle velocities and various levels of interference, w.r.t. the two performance metrics defined earlier. We vary the density of vehicles in the traffic jam, which contributes to the amount of background transmissions interfering with PVD transmissions and RSU beacon reception, the latter can result in postponing the reception of the RSU beacon by the reference vehicle. We vary vehicle speed (of the reference vehicle), which has an impact on the delivery probability; a higher speed increases the probability that the vehicle receives the message nearer to the RSU and decreases the number of periodic transmissions within the coverage area.

The FSR is determined by signal propagation, fading and interference. Propagation and fading are modeled with a dual-slope log-distance path loss model and a Nakagami fading model provided by NS-3. Most propagation model settings are taken from [57]. The parameters of the simulation model are given in Table 5.1.

### 5.3.5 Simulation Results

*Reactive Broadcast:* We start our discussion with the Reactive Broadcast (RB) strategy. Here, every received RSU beacon triggers a PVD transmission by the vehicle, as along as the vehicle is in range of the RSU. Figure 5.6 shows the spatial distribution of transmissions by the vehicle, grouped into 30 m bins and averaged over all simulations. It can be expected that the distribution of received beacons follows the FSR given by the propagation and fading model (cf. Figure 5.1). The figure shows that the absolute number of message transmissions increases (following the FSR curve) when coming closer to

[2] http://www.nsnam.org

| | | |
|---|---|---|
| Physical Layer | Antenna type | Omni-directional |
| | Antenna gains, cable losses | 0 dB |
| | Center Frequency | 5.9 GHz |
| | Channel bandwidth | 10 MHz |
| | Transmission Power | 10 dBm |
| | Energy detection threshold | -96 dBm |
| | MCS scheme | OFDM, 6 Mbit/s |
| | Path loss model | Log-distance with dual slope:<br>$\gamma_0$ = 1.9 up to 80 m<br>$\gamma_1$ = 3.8 beyond 80 m |
| | Fading model | Nakagami:<br>$m_0$ = 3 up to 50 m<br>$m_1$ = 1.5 up to 150 m<br>$m_2$ = 1 beyond 150 m |
| | Reference Loss | 48dB (at 1 m for 5.9 GHz) |
| | Noise Floor | -104 dBm (kTB) |
| | Receiver Noise Figure | 7 dB |
| MAC Layer | PSDU size | 400 bytes |
| | Frame duration | 672 $\mu s$ |
| | CCA threshold | -85 dBm |
| | Access Category | AC_BE (AIFSN=6, CWmin=15) |
| | Unicast retransmissions | infinite |
| Application Layer | Distance Threshold | 80 m |
| | RSU beacon frequency | 1 Hz |
| | Vehicle beacon frequency (background transmissions)<br>(background transmissions) | 10 Hz |
| Other | Lane length | 1500 m |
| | Reference vehicle speed | 10, 20, 30, 40 m/s |
| | Traffic jam density | 60, 120, 180, 240, 300 veh/km |
| | Simulation runs | 30 repetitions per speed-density-combination |

*Table 5.1: Evaluation Parameters.*

the RSU (distance=0 meters). At the same time the share of successful transmissions increases. This shows that trying to transmit at a large distance from the RSU is not efficient. This strategy suffers from huge number of unnecessary repetitions that increase the overall communication cost. Note that the sources of interference are uniformly distributed, therefore additional frame errors due to interference do not skew the shape of the distribution. As expected, RB has a very high success rate, as illustrated in Figure 5.9, where only a drop in the success rate can be observed at vehicle speeds of 40 meters per second. This is because at high vehicle speeds, only few RSU beacons are received, reducing the number of retries. Combined with high interference, this further reduces success probability.

*Immediate Broadcast / Unicast:* If the vehicle transmits the PVD packet immediately after receiving the first RSU beacon, we obtain a spatial distribution centered at 150 - 180 m (see Figure 5.7). This is far away from the RSU with the undesired effects mentioned before. Immediate Broadcast has a low success probability, while Unicast is successful at the cost of a large number of transmissions. Since we intentionally did not limit the

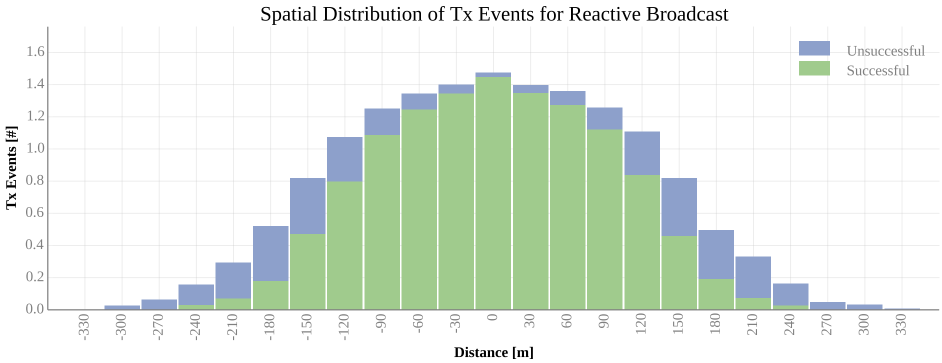


*Figure 5.6: Spatial distribution of transmission attempts for Reactive Broadcast (RB): The bars show the overall number of transmissions by the vehicle, thereof successful ones in green, unsuccessful ones in blue. Results include all speed and density combinations.*

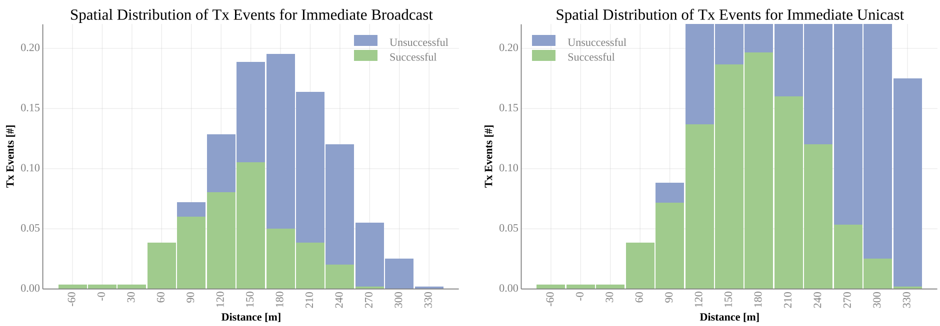


*Figure 5.7: Spatial distribution of transmission attempts for Immediate Broadcast (IB) on the left and Immediate Unicast (IU) on the right. Bars show the overall number of transmissions, thereof the successful ones in green, unsuccessful ones in blue. Results include all speed and density combinations.*

unicast retransmissions, we can observe a few cases with over 200 retransmissions necessary before a positive acknowledgment is received, which also indicates that the location of transmission is not suitable.

Figure 5.8 shows the Empirical Cumulative Distribution Function (ECDF) of the number of transmissions used in one unicast transaction. As the two evaluated *unicast* algorithms (IU, DU) are configured to have an infinite number of retransmission, all simulations resulted in a successful delivery of the PVD packet. The ECDF shows that Immediate Unicast needs around 10 retries in 80% of the cases, except for the low speed case (10 m/s), where more retries are necessary. This implies that a fixed retry limit of 10 messages would results in a success rate of 80%. By contrast, Delayed Unicast does not need more than 5 transmissions in neither of the considered cases.

*Impact of vehicle speed:* Figure 5.9 shows the impact of speed on the delivery success

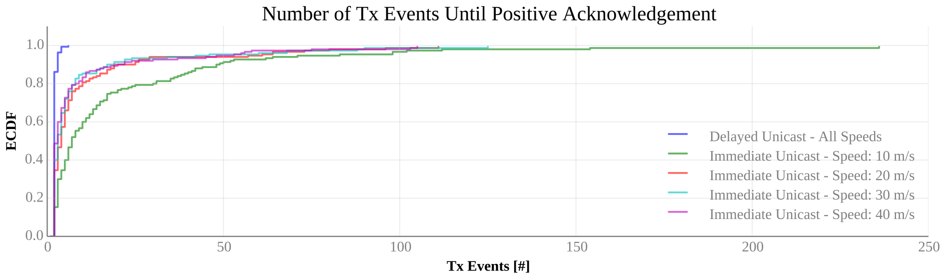


*Figure 5.8: ECDF of the required number of retransmission until successful delivery for the two unicast algorithms (DU and IU).*

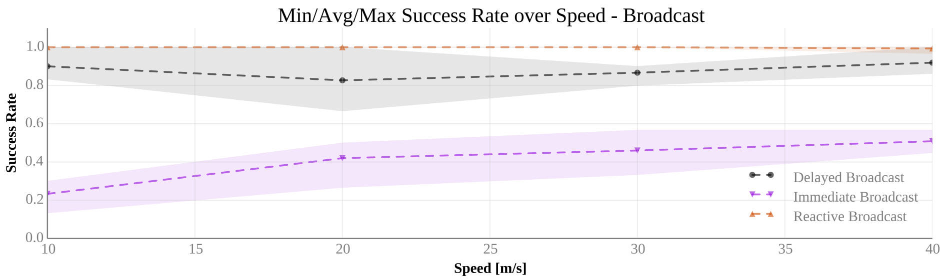


*Figure 5.9: Comparison of the success rate of the three broadcast algorithms; IB, DB and RB. The minimum and maximum values are represented by the bottom and top part of the shaded area for each point.*

rate for the broadcast algorithms (IB, DB, RB). Immediate and Delayed Broadcast use only one transmission attempt to deliver the PVD packet, while the number of attempts in RB depends on the number of received RSU beacons, i.e., as function of the speed and interference. If the vehicle drives into the coverage area, a high speed can results in that the vehicle can come closer to the RSU before receiving the first beacon[3], which triggers the PVD packet transmission. Since the used propagation loss model implies higher FSR closer to the RSU, the higher speed results in a higher success rate. The result for Delayed Broadcast shows again that postponing the communication to a location with better success probability is beneficial. This holds independent of the speed, as the disjoint curves for Immediate and Delayed Broadcast show.

Delayed Broadcast and Delayed Unicast wait for a better transmission location, therefore, the success rates are higher, as shown in Figure 5.10. Both strategies combine high success rates with low communication overhead. A small trade-off is visible, since unicast is always successful, but uses more messages than broadcast.

[3]For example, given a beacon broadcast rate of 1 Hz and a vehicle speed of 30 meters per second, the vehicle may receive the beacon within an interval of 30 meters, while at 10 Hz, the interval is reduced to 3 meters.

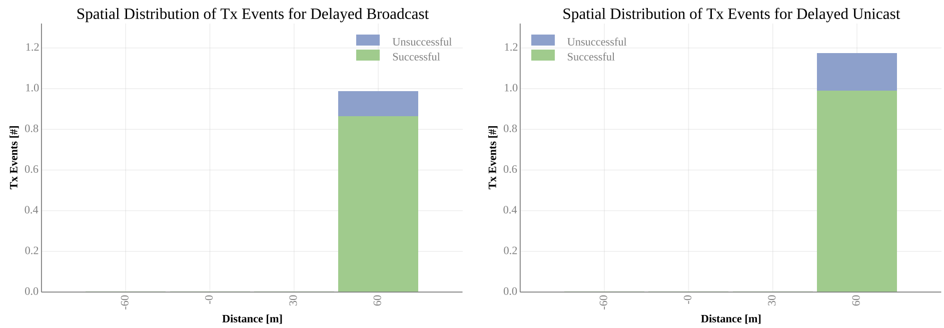


*Figure 5.10: Spatial distribution of transmission attempts for Delayed Broadcast (DB) on the left and Delayed Unicast (DU) on the right: Bars show overall number of transmissions, thereof successful ones in green, unsuccessful ones in blue.*

### 5.3.6 Overall Comparison of the Basic Algorithms

Figure 5.11 shows the measured success rate and absolute number of transmission events generated by each algorithm, averaged over all speed-density-combinations, respectively. While the unicast algorithms are always successful (due to unlimited retries), the success of the broadcast algorithms depends on the location and the repetitions. Reactive broadcast is nearly 100% successful, but at the cost of the highest number of transmissions used. By delaying the broadcast (IB vs. DB), the success rate can be more than doubled.

On the cost side, the unicast algorithms require more transmissions (due to retries), which is extreme if the PVD is transmitted immediately (Immediate Unicast). The Delayed Unicast achieves 100% success rate, and uses just 21% more transmissions than Delayed Broadcast, which delivers 88% of the messages successfully.

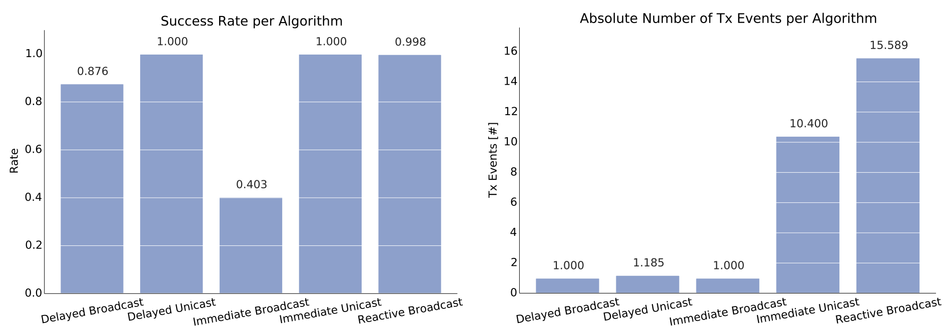


*Figure 5.11: Absolute number of transmissions generated by each algorithm over all speed-density-combinations.*

### 5.3.7 Discussion

The general trend shown in the results is that postponing the transmission attempts of PVD delivery, whether on purpose or due to chance (high interference or high speed and timing of beacons), improves the success rate. It has been also been shown that reacting immediately to the first beacon is either prone to delivery failures or requires a high cost to improve the success rate.

An intuitive option for reducing the impact of early reaction is to use an approach similar to WAVE, where it is possible to configure the number of beacons before switching channel. However, this approach could be unreliable for the scenario considered in this paper: At high speeds and low beacon frequencies the risk of there not being enough beacons arises; we observed simulations with only four beacons being received by the vehicle. At low speeds and high beacon frequencies, the progress of the vehicle towards the RSU between two beacons is of little significance. Additionally, complex road infrastructures make predicting when or if the delivery probability increases even more challenging.

For these reason we investigate how performance maps can be realized, and, while increasing the processing requirements at the RSU and requiring a slight but constant communication overhead for its dissemination, can reduce the channel load needed for the delivery of PVD.

## 5.4 Performance Maps

The aforementioned results show that it is beneficial to schedule a transmission so that a good transmission location is met. In our simulation model, the best transmission location is close to the RSU, since the FSR is increasing towards the RSU due to the chosen propagation and fading model. This might not always be the case, as illustrated in Figure 5.12. The figure shows the FSR calculated using NS-3 and using a Gilbert Model [54], trained on field trial measurements, the later showing that indeed high FSR variability can be experienced while traveling towards the RSU; therefore we propose that the area of best transmission locations together with a number of transmissions is included in the RSU beacon and indicated to the approaching vehicles. If this additional data is included in RSU beacons, it should be as compact as possible and have a constant length.

### 5.4.1 Data Acquisition and Representation of Performance Maps

The RSU is in a unique position of building up a performance map of its communication environment, especially when it comes to the estimation of reception probability in the case of V2I communication, by passively monitoring the periodic safety communication, e.g., CAMs or BSMs. These periodic messages contain position information from which

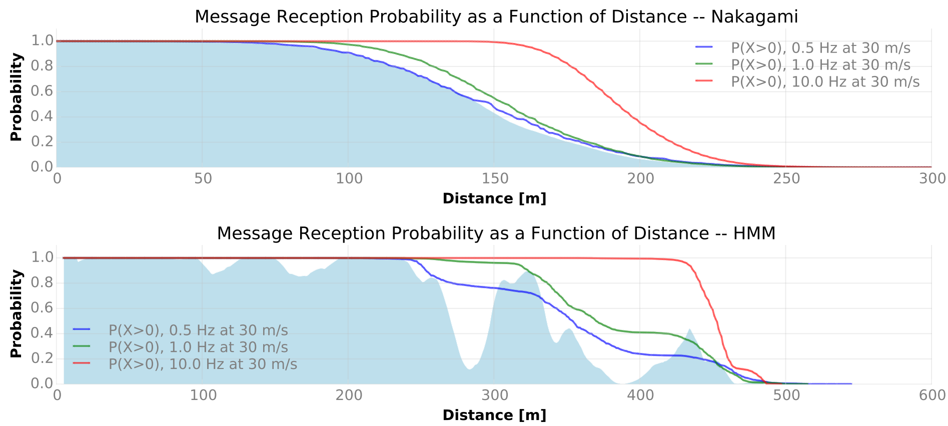


*Figure 5.12: Frame Success Ratio (FSR) and cumulative reception probability for receiving a RSU beacon versus distance to the receiver, if the FSR is given by a propagation and fading model (above: NS-3, below: Gilbert Model [54] based on field trial measurements).*

a histogram of successfully received transmissions and their originating locations can be generated (CAM or BSM as well as the ETSI GeoNetworking header contain position information). The histogram of received periodic messages from vehicles shows the range and best location for single PVD transmission. It can be represented as equal interval representation or as quantile representation as shown in Figure 5.13. Both representations have a constant size, which is beneficial when including it in a beacon message. Still, without FSR (=success probability) in a certain region, we do not know *how many* transmission attempts we need on expectation until we are successful. Therefore, we present a method for estimating the FSR in the following section.

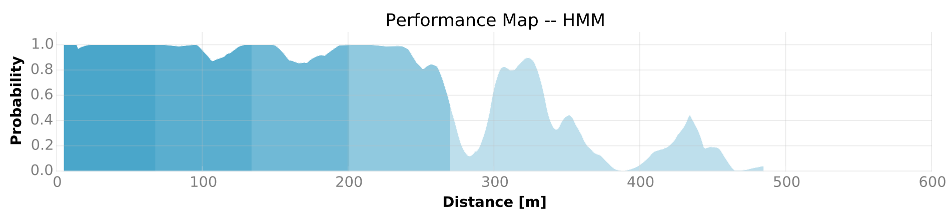


*Figure 5.13: Quantile (quintile) classification. The RSU coverage area is divided into intervals such that $1/5$ of the overall received messages fall into each interval.*

### 5.4.2 Estimating Frame Success and Adjusting Re-transmissions

Assume that $N$ vehicles are passing the RSU. Each vehicle sends a single PVD packet (via broadcast), which is received with probability $p$, which is the frame success ratio. Then

$p \cdot N$ is an estimate for the expected number of messages, but neither $p$ nor $N$ are known to the RSU. If each vehicle sends the message *twice* in short succession, then the RSU can count the number of cases of receiving one message ($x_1$) or two messages ($x_2$) from the same vehicle. This allows to calculate an estimate of $p$ directly or indirectly via $N$, which we explain in the following.

### Estimating the Frame Success Probability ($p$)

Let $X$ be a random variable for the number of messages received from a single vehicle, and $p$ the success probability for successfully receiving a message in a certain region. Then $X$ is binomially distributed, $X \sim Bin(2, p)$, with

$$P[X = 0] = (1 - p)^2 \tag{5.6}$$

$$P[X = 1] = 2p(1 - p) \tag{5.7}$$

$$P[X = 2] = p^2 \tag{5.8}$$

For $i \geq 1$ the RSU can count the number of vehicles $x_i$ from which exactly $i$ messages are received. As each vehicle generate two transmissions, we calculate $x_2$ by

$$x_2 = 2N \cdot P[X = 2] = 2Np^2 \tag{5.9}$$

We calculate $x_1$ as follows and substitute $2Np^2$ by $x_2$:

$$x_1 = 2N \cdot P[X = 1] = 4Np - 4Np^2 \tag{5.10}$$

$$\Rightarrow \quad x_1 = 2\frac{x_2}{p} - 2x_2 \tag{5.11}$$

We can use this to derive an estimate for $p$:

$$\hat{p} = \frac{2x_2}{x_1 + 2x_2} \tag{5.12}$$

Using this estimate $\hat{p}$ of the frame success probability, the RSU can request the vehicles to send $m = \lceil \frac{1}{\hat{p}} \rceil$ messages in order to be able to successfully receive one message per vehicle on average.

Having $m$ instead of 2 transmissions changes the calculation above. For $m$ transmissions per vehicle, Equation 5.12 can be generalized to

$$p = \frac{2x_2}{(m-1)x_1 + 2x_2} \tag{5.13}$$

Here, only the numbers $x_1$ and $x_2$ of vehicles are considered, from which one or two messages are received. Note, that in most cases there are no more than 3 message transmitted per vehicle, because the number of retries $m$ is chosen inversely proportional to $p$. Thus, $X$ is binomially distributed with $p = 1/m$ and $\mu = mp = 1$, and from Markov's inequality follows that $P[X > 3] \leq \frac{\mu}{3} = \frac{1}{3}$. Thus we can assume that the two counters $x_1$ and $x_2$ cover a reasonable part of the distribution.

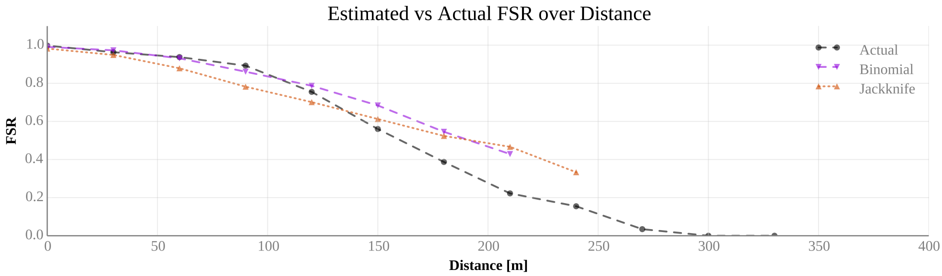


*Figure 5.14: Comparison of the actual FSR over distance to the RSU with the estimated FSR based on the Binomial distribution and the Jackknife method as described in Section 5.4.2. The actual values are the ratio of successful transmissions over all transmissions at a certain distance bin. For the estimators, each point of the plot represents the estimation based on two PVD transmission per vehicle ($m = 2$) within a distance bin. Missing values at high distances are due to insufficient data collected. The strategy to increase re-transmissions is not applied here.*

### Estimating $p$ via the Number of Vehicles ($N$)

The number of observations $S_{\text{PVD}} = x_1 + x_2$ is a simple estimator, but is has a bias because of the unknown number $x_0$ of vehicles with no successful transmission. If we count the number $S_b$ of distinct MAC addresses of safety beacons, which vehicles are supposed to transmit at frequencies of 1-10 Hz, we can obtain a simple estimate $\hat{n} = S_b$ for the overall number of vehicles. Since these beacons have a different size than PVD packet, this does not allow to estimate the probability $p$ for PVD transmissions but to estimate $N$, from which the estimate $\hat{p}$ can be derived by

$$\hat{p} = \frac{\text{received messages}}{\text{estimated total messages}} = \frac{x_1 + 2x_2}{2\hat{N}} \tag{5.14}$$

Safety beacons are transmitted at higher frequencies than PVD packets and give larger sample sets. However, if not every vehicle passing by an RSU intends to deliver a PVD packet, this method would give an estimate for the wrong population.

The problem of estimating $N$ from the outcome of two samples is closely related to capture-recapture problems in biology [58] and has recently been addressed to estimating vehicles from safety beacons [59]. This can be directly applied to reduce the bias of $S_b$ from counting safety beacons, but it does not solve the “wrong population” issue. It should be rather directly applied on the samples of PVD receptions, i.e. based on $x_1$ and $x_2$. Using the Jackknife estimator for two “captures” from [58] gives the following estimator:

$$\hat{N}_{J2} = S_{\text{PVD}} + \frac{1}{2}x_1 = \frac{3x_1 + x_2}{2} \tag{5.15}$$

Using Equation 5.14 we obtain an estimate for $p$:

$$\hat{p} = \frac{x_1 + 2x_2}{2\hat{N}_{J2}} = \frac{x_1 + 2x_2}{3x_1 + 2x_2} \tag{5.16}$$

### Evaluation of Frame Success Probability Estimation

Figure 5.14 compares the actual success probability (FSR) with the two aforementioned estimators based on the Binomial distribution and based on the Jackknife method. The figure shows the outcome of the estimation when two samples, i.e. two PVD transmissions, are taken at different distances from the RSU. The figure shows a reasonable accuracy of both estimators for regions of high FSR, and a growing inaccuracy when the FRS decreases and thus less data elements are available. The results also show that the Binomial estimator slightly overestimates the probability, while the Jackknife estimator underestimates the probability for high probabilities. Considering the high estimator accuracy for high success probabilities supports the argument that PVD transmissions should be scheduled within the best performance region.

The calculations above assumes a uniform success probability $p$ within a certain area, and that vehicles uniformly chose their transmission location within that area. The Jackknife method assumes closure of the experiment, which is reasonable if the time intervals of data acquisitions are small. Deviations from this assumption need to be considered in the calculation, e.g. the success probability $p$ should be made dependent on the message size, if the PVD packet size varies.

## 5.5 Conclusion

We have studied the delivery success probabilities of various algorithms for delivering PVD from the vehicle to the RSU and shown that the communication overhead can be significantly reduced by utilizing low overhead performance maps or indicators defining the areas with the highest delivery rate. Performance maps are especially applicable in vehicle-to-infrastructure communication, since the positions of the vehicles always follow the same road geometry, which allows a very compact representation. Furthermore, we showed how performance maps can be used to boost PVD delivery success, even if unacknowledged broadcasts are used: By advising approaching vehicles to repeat their broadcasts based on estimates of the frame success probability within the best performance region, we can expect to successfully receive one message per vehicle on average. From the considerations above, we conclude the following:

- RSU beacons should include a region of optimal transmission performance, which is at least specified by a distance interval.
- As long as broadcast transmissions are used, the RSU beacons should also include the number of PVD transmission repetitions. Approaching vehicles that received these beacons and have PVD packets to transmit should follow the repetition policy.
- From counting the received PVD transmissions, the RSU should constantly estimate the success probability (which might change as traffic density and channel load changes) and adjust the number of PVD transmissions, as exemplified in Section 5.4.2. Focusing on the area of best transmission locations allows better estimates and smaller numbers of transmissions.

From a dissemination point of view, i.e., the RSU broadcasting information to all nearby vehicles, the RSU can use the local histogram that is used to generate the performance maps and either the current or estimated speed of the surrounding vehicles to estimate the optimal repetition rate for broadcasting the message. This approach is mostly beneficial when the amount of information the RSU must disseminate and the density of vehicles are high, such that as many vehicles as possible are informed while consuming the minimum amount of communication resources.

Though we presented a quite complete solution for notifying vehicles, evaluating their responses and adjusting the suggested broadcast repetitions, this is only a first step that hopefully triggers further research, e.g. considering PVD packets of variable size, PVD packets spanning multiple messages, or adjustments of the suggested number of broadcast transmissions in order to limit a negative impact on channel load. Additionally, we need to analyze how to cope with special cases such as complex road infrastructure, where the RSU covers multiple entry road.

# Chapter 6

# *Extending Road-side Unit Coverage through Geographic Routing*

In this chapter we investigate how the communication range of Road-side Units (RSUs) can be extended when dissemination and collecting information to and from vehicles, using other vehicles as intermediate forwarders. This is needed as vehicles may experience extended periods without direct connectivity with the RSU, and allows the RSU to interact with vehicles independent of its geographic position. To extend the communication range we investigate two graphic routing algorithms, Greedy Forwarding and Contention-based Forwarding (CBF), and improve them w.r.t. delivery rate and communication overhead.

The content of this chapter is based on [2], which has been extended with additional background information to explain the performance of CBF. In addition, we have added the performance evaluation of Greedy Forwarding as it is also considered a candidate for geographic routing by ETSI.

## 6.1 Introduction

Vehicles driving throughout the road infrastructure, periodically generate Probe Vehicle Data (PVD) samples and store them locally until they can be uploaded at a RSU. When using Controlled Probing, as described in Chapter 4, vehicles should be able to receive management messages from the RSU that instruct them whether, and if so, what and how to generate probes. PVD collected using a RSU based infrastructure is therefore restricted by the density and geographic distribution of RSUs throughout the road infrastructure, potentially leading to a delay, as documented in Chapter 3, in when the information can be delivered. To reduce the dependency on the RSU distribution, i.e., their availability at specific locations, we extend their communication range by using vehicles equipped with On-Board Unit (OBU) as forwarders, enabling messages to be routed between two geographic locations. This also reduces the collection delay from the time a probe is generated and until it is delivered at the RSU, if enough vehicles re available to create a path from where the probe is generated to the RSU.[1]

A large amount of Vehicular Ad-hoc Network (VANET) applications depend heavily on geographic relevance. Information for both safety and traffic management applications is mainly relevant in the immediate vicinity in the forward driving direction of the vehicle, meaning that information usually has to be disseminated in the *upstream* traffic direction. For drivers to be able to use an alternative path that avoids an upcoming congestion, they need to be informed before they arrive at the nearest intersection. Therefore, event information is usually sent from the location area, if detected by a vehicle, or from a RSU, if we use the infrastructure to dissemination information, to a specific location, which we name the destination area. Due to this relationship we restrict this work to looking at the subset of routing protocols to geographic routing. In particular, we focus the evaluation on two geographic routing algorithms that are part of the normative parts of the ETSI ITS-G5 stack [60] and identifies potential pitfalls that can reduce End-to-End (E2E) delivery and cause uncontrollable behavior. Two alternative algorithms are proposed and evaluated w.r.t. to their reliability performance and communication overhead that achieve both improvements in E2E success and communication overhead, by introducing minimal modification. The scenario considered here is limited to the generalized concept of sending a message from a geographic point A to a geographic point (or area) B. The message exchange with the RSU, depending on whether the message is destined to or originate from the RSU, is assumed to be performed using performance maps as is shown in Chapter 5, due to differences in the requirements.

Figure 6.3 shows a simplified example with one vehicle shows the concept and the roles involved. The *source* generates a probe and uses two intermediate nodes, called *forwarders*, to deliver the message to the *destination*, i.e, the RSU. We consider the message being successfully delivered when it is delivered inside of the green area, and expect that performance maps, as defined in Chapter 5, provide reliable communication for the last Vehicle-to-Infrastructure (V2I).

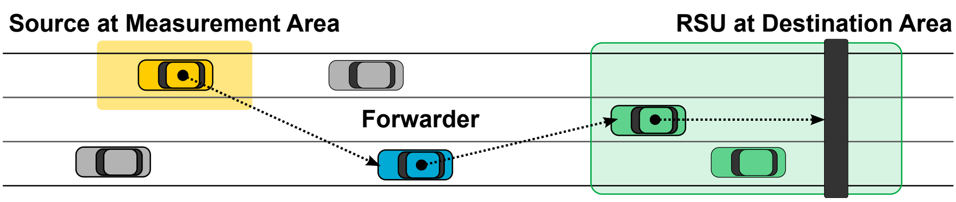


*Figure 6.1: The illustration shows how geographic routing can be used to forward PVD through V2V2I communication to a RSU, thereby reducing the impact of travel time between RSU on the collection of PVD.*

[1] When a route is not available, vehicles can temporarily store probes until a potential forwarder becomes available, however, in this work we focus on the forwarding aspects and performance.

## 6.2 Problem Formulation, Statement and Contributions

Conventional geographic routing has three prerequisites when making routing decisions [61]:

1. Own geographic position – Vehicles with OBUs are equipped with Global Navigation Satellite System (GNSS) devices, so this information is available to the vehicle.
2. Position of the neighbors – Vehicles continuously exchange position information through safety beacons, so the neighborhood information is constantly updated and allows them to make decisions regarding the next hop. This is needed to compare progress of each neighbor towards the destination.
3. Position of the destination – This is determined by the application and must be known by the vehicle. E.g., PVD management messages are disseminated to the area of interest or PVD messages are disseminated to the location of an RSU.

The vehicular environment is dominated by high mobility of the vehicles, making the second point in the above list a challenge: While new neighbor vehicles are actively detected through beacon reception, the challenge is to be able to recognize when a given neighbor has left the neighborhood, and that a lack of beacons is not caused by interference or the vehicle changing the frequency of messages. In ITS-G5, safety beacons do not contain sequence numbers, increasing the challenge.

Updating the neighborhood information using safety beacons can be unreliable, when the frame size of the messages used to populate the neighborhood information differs from the frame size of outgoing messages, as they have unequal reception probability. This reduces the value of the neighborhood information, especially when the outgoing frames are larger. Additionally, if the neighborhood information is used to identify the forwarder that optimized the number of hops using distance as a metric, the probability of interference due to the hidden node problem is increased.

Typical key performance metrics for routing protocols are successful E2E delivery and overhead costs, i.e., number of hops, total number of messages, channel load increase, delay, etc. In Intelligent Transportation System (ITS) scenarios, however, the prioritization is different. When the communication resource is shared with e.g., safety communication, it is essential that the overhead of non-safety communication is kept at a minimum, predictable and controllable. E2E delivery success, while important, has a lower priority, due to the dynamic properties of traffic. E.g., the above mentioned traffic congestion changes rapidly making the disseminated information obsolete and replaced by updated information. Similarly in the case of individual PVD samples, it can be expected that the information will be updated when the next capable vehicles passes by.

### 6.2.1 Contributions

The contributions of this chapter are the following

- In-depth review of the currently proposed algorithms for geographic routing in ETSI ITS-G5 networking stack and identification of possibilities of unexpected behaviour.
- Introduction of two minimal modifications that improve E2E delivery through low and predictable communication overhead.
- Simulative comparison showing that the proposed modification improve reliability and, in most cases, have a lower communication overhead than the default approaches.

## 6.3 Related Work

Mobile Ad-hoc Network (MANET) routing algorithms can be classified as pro-active (table-driven) and reactive algorithms. Completely reactive algorithms such as Dynamic Source Routing (DSR)[62] flood the network with control messages, so called route requests, to find a path to the destination. Once a route has been identified, the source can reach the destination by sending packets containing the full source-destination path, as long as the topology is stable. This can lead to high header overhead, as the full path needs to be contained in each message and high message overhead due to flooding for the route discovery. Table driven algorithms maintain routing tables and update them dynamically as the network topology changes. Both approaches have disadvantages with topology changes. While reactive algorithms have a high message overhead per route due to flooding, table-driven algorithms are usually slow in propagating information about topology changes. Some ad hoc routing algorithms, such as Dynamic MANET On Demand (DYMO), combine on demand route discovery with table-driven route maintenance and route repair functionality. However, in VANET topology changes can be expected to be extremely fast, so aforementioned algorithms could not even finalize the route discovery phase before the topology changes occur. This is a disadvantage of address-based routing in highly dynamic networks. The majority of VANETs use-cases target disseminating information to or in geographic areas, agnostic of the node address. Furthermore, nodes typically have access to positioning information. Position information can be used for multi-hop routing and information dissemination in VANET.

Position based or geographic routing was first described in [63] for fixed networks and for packet radio in [64], defining the three prerequisites: 1) own geographic position, 2) position of the neighbors and 3) position of the destination. CBF depends on 1 and 3, due to a realization that 2 can be inaccurate, due to miss-match probability. The original CBF approach was proposed independently in [65] and [66]. CBF does indeed provide the optimal communication overhead, but only when message sequencing is guaranteed. The proposed method investigates how CBF can be realized without compromising the low communication overhead while relaxing the assumptions regarding message sequencing. Other CBF variants that focus primarily on improving reliability, mainly through additional control messages or optimizing the forwarder selection. BOSS, [67], uses CBF to disseminate large packets first, i.e, the data rather than control messages, and then uses explicit acknowledgments to confirm that the message has been received. The main focus is on providing reliable E2E communication by using control messages. Also, it zones the forwarding area to reduce communication overlap. An approach the could also be applicable in the proposed solution to distribute the forwarding in time, and reduce probability of overlap.

[68] presented the original version of Greedy Forwarding, using neighborhood information for selecting the optimal forwarder to progress the message towards the target. While the neighborhood information improves the progress by selecting the best forwarder it depends on the neighborhood information being up to date. In a highly mobile environment, this can be challenging. In addition, variable messages sizes, equipment etc., can make the information unreliable. Therefore, the work here focuses on an opportunistic approach.

Most recent work on the evaluation of routing protocols defined in ETSI GeoNetworking has been published in [69], that was published shortly after the submission of [2]. While evaluating the general routing properties of GeoNetworking algorithms, they identify and conclude that the CBF contention timer needs to take the Media Access Control (MAC) layer delay into account when broadcasting. W.r.t. Greedy Forwarding, their recommendation is not to use nodes in what they define the 'grey zone', i.e., the outer perimeter of a nodes communication range due to low success probability when forwarding to the next hop. This work evaluates a simpler topology and scenario, which provides insight into the mechanisms of the algorithms and their performance as well as proposing and evaluation a solution that is robust towards the identified issues.

## 6.4 Review of ETSI ITG-G5 Geographic Routing Algorithms

ETSI ITS-G5 defines three geographicly oriented communication primitives, listed in Table 6.1, and two geographic routing algorithms that can be used to realized them [60]. These communication primitives are enabled by the networking layer, as illustrated in Figure 6.2. Applications and facilities can use these primitives to disseminated information to specific locations throughout the road infrastructure. Figure 6.3 shows an example of GeoBroadcast (GBC), where a message is routed from the source to all vehicles within the destination area.

Before describing and discussing the algorithms that enable geographic routing, we first

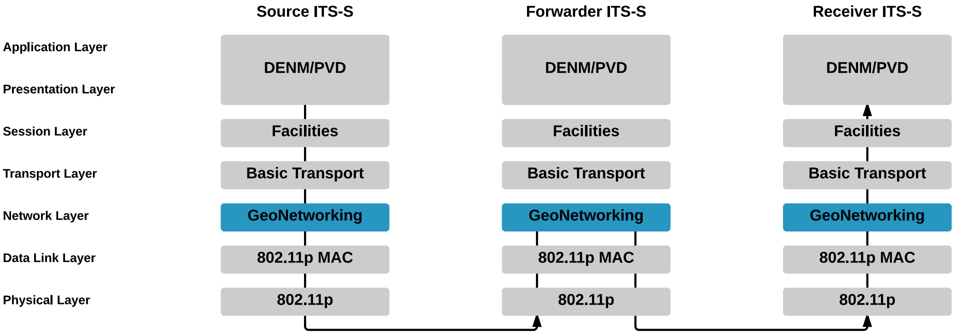


*Figure 6.2: ITS-G5 communication layer overview. GeoNetworking is part of the ITS Networking and Transport layer, between the BTP layer and the MAC layer.*

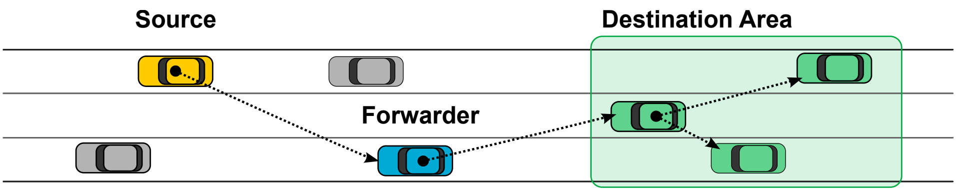


*Figure 6.3: The GeoBroadcast consist of two parts; routing from the source to the destination area and dissemination of the message within the area.*

| Primitive: | Definition: |
|---|---|
| **GeoBroadcast (GBC)** | Allows for a vehicle to target a specific geographic area and deliver a message to all vehicles within that area. The functionality is based on Greedy for the forwarding and different variations of CBF for the *dissemination* |
| **GeoUnicast (GUC)** | GeoUniCast allows one ITS-Station (ITS-S) to address another, specific ITS-S. The message is forwarded towards the destination via forwarding ITS-Ss and only delivered to the addressed node. The main use-case for this approach is where a Roadside-ITS-Station (R-ITS-S) needs to reply to a Vehicle-ITS-Station (V-ITS-S) request by allowing to provide the vehicle with the message even when it leaves the coverage area of the R-ITS-S. The application of this is however dependent on how often the vehicle changes its pseudo-ID/address, as the address is required. |
| **GeoAnycast (GAC)** | Similar to GeoBroadcast, but rather than delivering the message to all vehicles within the specified area, the routing is considered to by successful when *any* vehicle within the geographic destination area has received the message. |

*Table 6.1: Overview and definition of the different communication primitives provided by the GeoNetworking Layer in ITS-G5. GAC, GUC and GBC depend on* routing *functionality.*

discuss the general functionality of GeoNetwork, the umbrella term used in ETSI documents, as the two algorithms are closely bound to the operation that occur here.

### 6.4.1 General Functionality

GeoNetworking allows an application to specify what to do with a message w.r.t. a) how to send it, i.e., accordingly to the three primitives defined above, and b) where to send it, the geographic location for which it is relevant.

To provide its functionality, the GeoNetworking layer only needs to check how to process a message and to maintain the neighborhood information. The update of the neighborhood table is of particular importance in the context of geographic routing, as it is used as input by two routing algorithms. Either as direct input to provide a pool of candidates that can be used as forwarder or to decide not to forward if the neighborhood information does not contain any neighbors. Figure 6.4 and Figure 6.5 show the high level logic of send and receive operations.

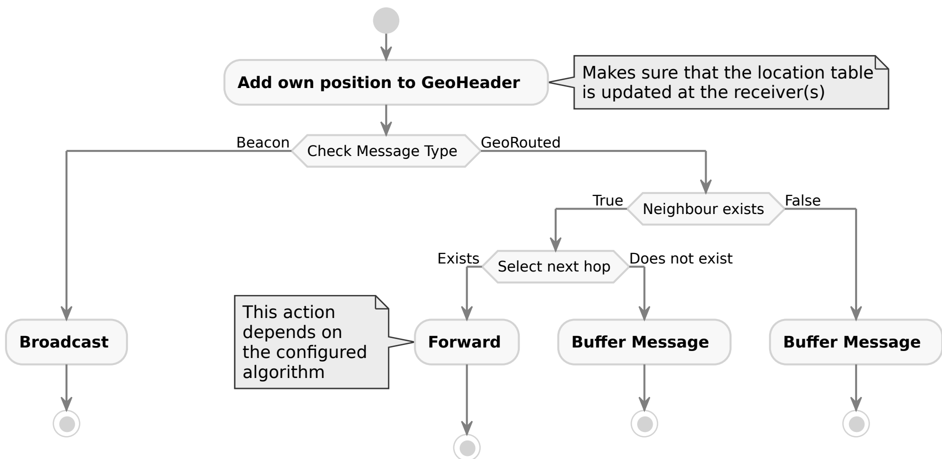


*Figure 6.4: Generalized GeoNetworking send operation – Depending on the message type, the message is either broadcast of forwarded, depending on the forwarding algorithm.*

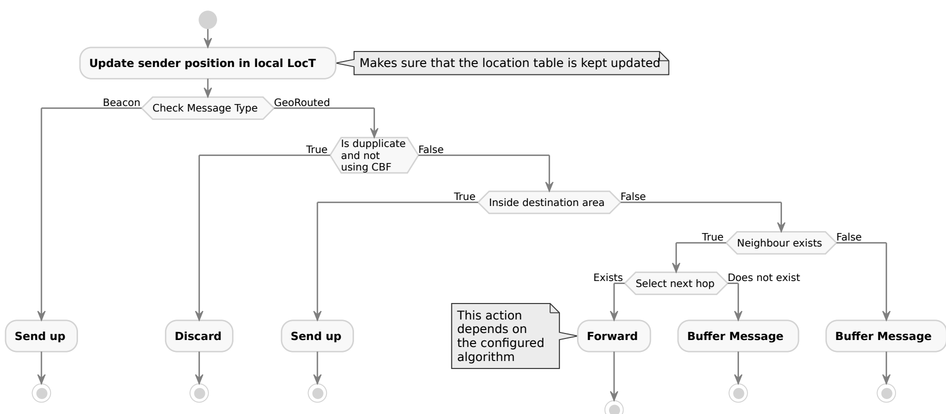


*Figure 6.5: GeoNetworking resides in the ITS Network and Transport layer, providing GeoNetworking functionality for the upper layers and manages forwarding.*

It is worth noting, that while the neighborhood information is *updated* on the reception of a message, the current GeoNetworking standard [60] does not specify how it is maintained, i.e., when nodes are *removed*. Additionally, GeoNetworking does not provide E2E acknowledgment of message delivery, which means that reliability, if needed, needs to be implemented in upper layers. Finally, two mechanisms are defined for the duplicate detection mentioned in Figure 6.5: The time stamp or the time stamp and sequence number of the received message[60]. This is problematic in the context of geographic routing where messages can be received out of order due to various circumstances, e.g., mobility forces the messages to travel via different routes, and if a source vehicle generates more than one message; all message failing the duplicate detection are discarded. I.e., in the case that one source has generated two events, one about end of congestion and one about a potential alternative route, only one is being recognized if they arrive out of order.

### 6.4.2 Greedy Forwarding

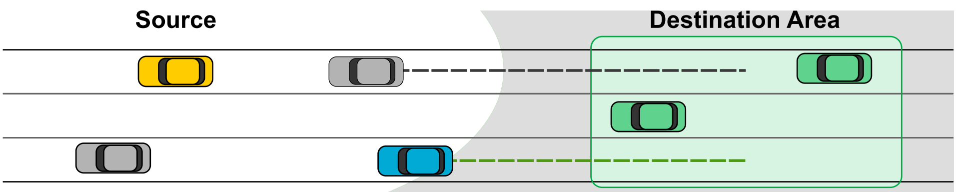


*Figure 6.6: Greedy Forwarding selects the forwarder based on the which node provides the highest progress towards the destination area. The green line indicates the most progress.*

Greedy Forwarding is a unicast based algorithm, which applies the *line forwarding* policy to select the next hop. This means that for each hop, the algorithm selects the next forwarder among the local node's current neighbors[2], based on the criterion of which node provides the largest progress towards the destination area.[3] The message is sent using unicast by addressing the next forwarder's MAC, according to the MAC layer type and configuration used, e.g., with the configured number of retries or priority queues. A visual example of Greedy Forwarding is illustrated in Figure 6.6 and a simplified reproduction of the algorithm is illustrated in Figure 6.7.

Greedy Forwarding has a few potential limitations and complications that reduces the E2E success rate. As discussed in both Chapter 2 and Chapter 5, 802.11p suffers from high Frame Success Ratio (FSR) at the edge of the communication range due to interference and propagation loss. Therefore, selecting the node furthest away from itself, the delivery probability decreases. As a side effect, and because Greedy Forwarding uses unicast, this causes the MAC layer to fully utilize the maximum number of retries, creating

[2]The neighborhood information is provided and updated by the GeoNetworking layer.

[3]In case no suitable forwarder can be found, the message is buffered until a GeoNetworking message is received, implicitly implying a potential forwarder.

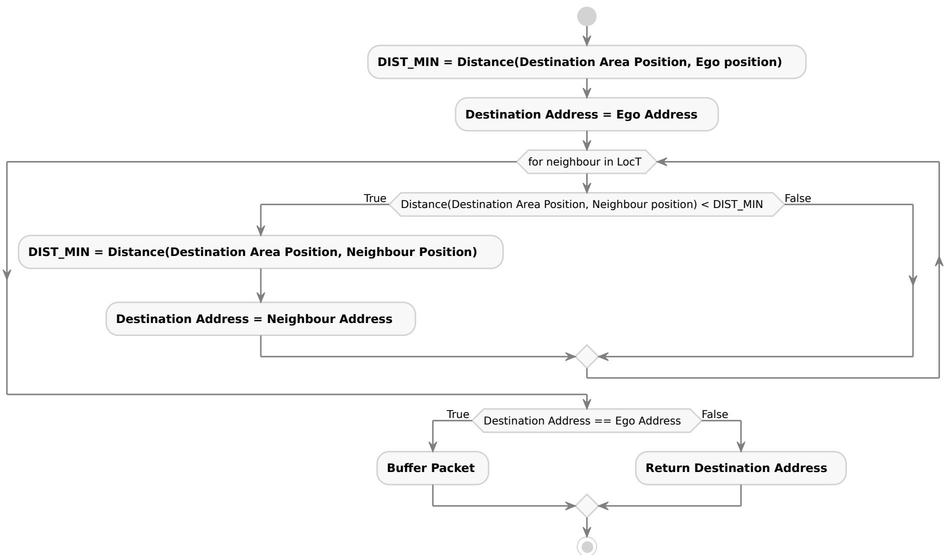


*Figure 6.7: Greedy Forwarding – Simplified reproduction of the Greedy forwarder selection algorithm. The Distance-function is based on the Euclidean distance. The figure is based on the representation of the Greedy Forwarding algorithm in Appendix D.2 in [44]*

additional, unnecessary channel load and interference while at the same time queuing up other messages locally.[4] The queuing of other messages can potentially lead to significant complication with respect to the delay of safety messages. Inaccuracies in the neighborhood information, due to position updates or even pseudo-address changes, can lead to similar consequences, making Greedy Forwarding highly dependent on the content of the neighborhood information and that this information is accurate.

### 6.4.3 Contention-based Forwarding

Contention-based Forwarding uses broadcast as opposed to Greedy Forwarding's unicast based approach; each node that receives a message can be the forwarder and competes against the others. This is motivated by the problem of maintaining an up-to-date neighborhood table thus making CBF independent of the neighborhood information accuracy. The forwarder selection in CBF is illustrated in Figure 6.8 and explained in further details below.

The forwarding competition is designed such that the node that can provide the largest progress towards the destination area compared with the sender[5], wins. The progress is

[4]Draft version of [70] mentioned Quality of Service (QoS) functionality with multiple queues and unacknowledged unicast communication, but in the most recent version, [71], this functionality has been removed.

[5]During forwarding, there is no difference between whether the message was received from the source or a forwarder, thus sender covers both node types.

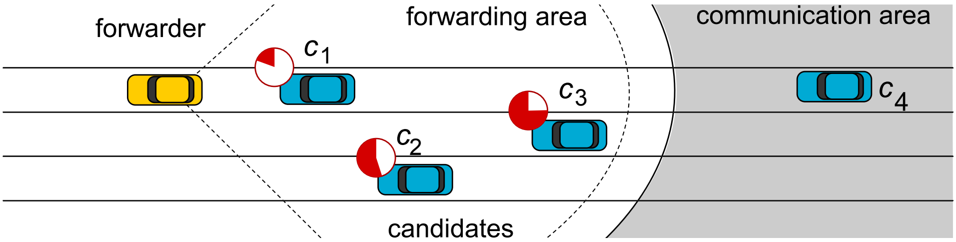


*Figure 6.8: Visualization of the forwarder selection in the CBF algorithms. Each vehicle calculates a time-out based on the progress towards the destination.*

calculated by each candidate as:

$$PROG = Distance(\text{Destination Area, Sender}) - Distance(\text{Destination Area, Ego Position}) \tag{6.1}$$

where the ego position is the position of the potential candidate. If the progress is less than zero, the node ignores the message, as it does not contribute. Nodes with a progress larger than zero, calculate a contention time-out using:

$$TO\_CBF = \begin{cases} TO\_CBF\_MAX + \dfrac{TO\_CBF\_MIN - TO\_CBF\_MAX}{DIST\_MAX} \times PROG & \text{for } PROG \leq DIST\_MAX \\ TO\_CBF\_MIN & \text{for } PROG > DIST\_MAX \end{cases} \tag{6.2}$$

where $TO\_CBF$ is the contention duration, $TO\_CBF\_MAX$ and $TO\_CBF\_MIN$ define the upper and lower bound of the contention duration and $DIST\_MAX$ is the assumed maximum communication range. All values are static and pre-configured at the OBU. The above equation is plotted in Figure 6.9, and is a linear function of the progress calculated in Equation 6.2.

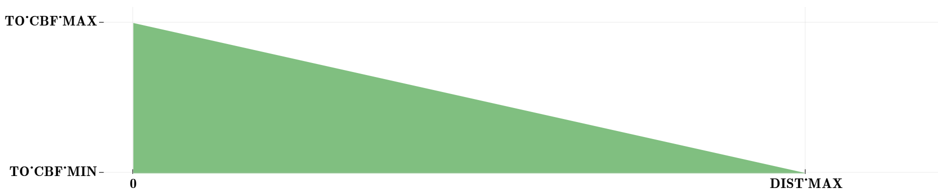


*Figure 6.9: Relationship between $DIST\_MAX$, $TO\_CBF\_MIN$ and $TO\_CBF\_MAX$. The x-axis is the progress and the corresponding value on the y-axis is the contention time-out between the minimum and maximum values.*

The contention delay, $TO\_CBF$, defines when the candidate node must re-broadcast the received messages, resulting in the node forward the message. The key concept is that if a node participating in the contention receives the message *before* its own timer has triggered, the node drops out of the contention and deletes the message. The assumption used here is that the node that transmitted the message first must have had a lower contention duration, thus a higher progress. This, theoretically, maximizes progress while minimizing communication overhead.

The whole process is visualized in Figure 6.10 and repeated until the message arrives at the destination area. I.e., if the receiving vehicle is within the destination area, the message is either consumed or disseminated, depending on the used communication primitive.

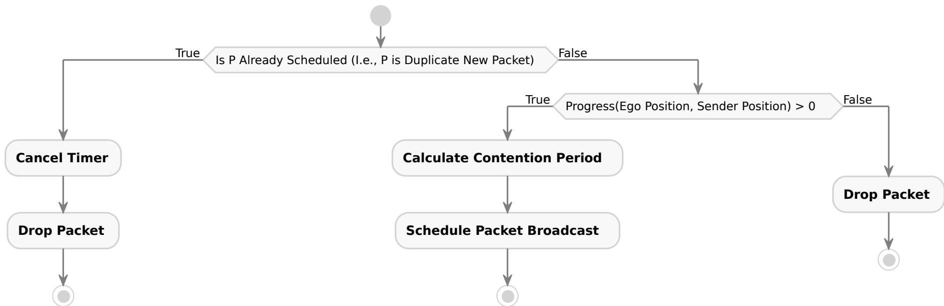


*Figure 6.10: Simplified reproduction of the CBF algorithm. Progress is calculated accordingly to Equation 6.1*

We spend the next two section on discussing a potential weakness in the CBF algorithm as well as the impact of the static definition of variables used in the calculation of the time-out.

### Timing and Assumptions

CBF is based on assumptions that the lower layers behave deterministically and that the communication is instantaneous. As a results, CBF can behave unintentionally under certain circumstances.

MAC layer delay, due to queuing, contention, etc., can result in nodes, which are reasonably close to each other, to all forward the messages, i.e., queue it at the MAC layer, resulting in multiple duplicates being broadcasted. Depending on the number of duplicates a potential forwarder receives, CBF will either assume that a better candidate has forwarded the messages, and therefore drop-out of the forwarding, or restart the forwarding process, generating unnecessary duplicates. Generally, an even number of duplicates results in dropping out and an uneven number results in a restart.

Stochastic behavior in the communication can result in unnecessary communication overhead. For examples, if the communication range of the source is longer than the communication range of the receiver it is possible that neighbors in close vicinity of the sender receive the message from the sender but not from the forwarder (the new sender). This results in the neighbor assuming that it is a forwarder, if it has not received a message indicating otherwise, and broadcasting the message. This message restarts the forwarding.

### Impact of Static Parameters

Equation 6.2 uses a static, theoretical maximum communication range, $DIST_{MAX}$ as a cut off threshold. This can lead to unwanted side-effects if it is either significantly overestimated or underestimated. If $DIST_{MAX}$ is underestimated, there is a higher probability for nodes outside of $DIST_{MAX}$ receive the message. All these nodes default to $TO_{MIN}$, increasing the probability of collisions between two transmission of the message, or that both messages are transmitted, which, as discussed above, can lead to a self-cancellation. Over estimation of $DIST_{MAX}$ leads to a loss in resolution as the lower part of the available contention range is never used, as illustrated in Figure 6.11. I.e., all contention values are pushed towards the maximum, $TO_{MAX}$, value, unnecessary increasing the E2E delay, which accumulates over each hop, and b) increases the probability of multiple vehicles transmitting at the same time, which again leads to the algorithm self-cancelling.

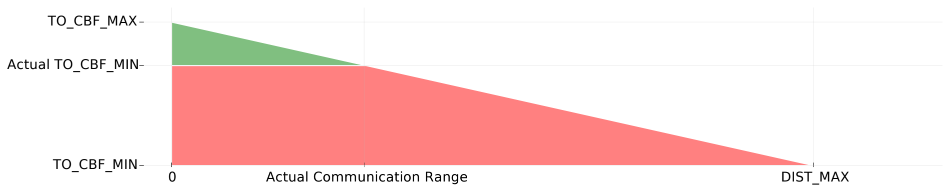


*Figure 6.11: Impact of overestimating $DIST\_MAX$ and its impact on the contention window.*

### Stop Criteria

As CBF relies on implicit acknowledgments, two issues arise in the vicinity of the destination area, depending on whether the message is consumed or disseminated within the destination area. If the message is disseminated, everything works fine, as the defined mechanism identifies 'better' forwarders and thus stops its own forwarding. However, if the message is consumed by the vehicles within the destination area, the vehicle just outside of the border of the destination area will *always* repeat the message, no matter how much progress they contribute, as no other forwarder broadcasts the message.

A wrongly configured destination area, i.e., a destination area that is smaller than the communication range of the nodes, can additionally enhance this problem by creating a ping-pong effect on either side of the destination area. When the vehicles do not keep track of which messages they have processed, each broadcast is treated as a new message, why the ping-pong effect will continue until the vehicle nearest to the border of the destination area broadcasts the message or the maximum hop count is reached.

### 6.4.4 Summary

Both the considered algorithms, Greedy Forwarding and CBF, are designed to provide optimal per message progress, and achieve this by selecting the next forwarder within their own communication range that provides the most progress towards the destination, either explicitly or implicitly. However, overly optimistic assumptions on communication performance and message sequencing make the algorithms fail when either of the two assumptions does not hold.

Greedy Forwarding is vulnerable due to an unaligned probability of symmetrical communication; the probability of receiving at least one message from a potential forward through a broadcasted beacon message is in certain situations larger than the probability for the vehicles being able to send a message back. E.g., stationary traffic due to congestion or two vehicles traveling at the same speed, at a distance corresponding to the communication radius.

CBF does not depend on the neighborhood information except to decide if there are any neighbors, i.e., potential forwarders. Instead, it uses the message itself for selecting the best forwarder within the node's neighborhood. This reduces the impact of unequal reception probabilities depending on messages size and fast topology changes. However, assumptions with regards to correct and timely message ordering makes the algorithm cancel itself out, if, for any reason, a node using the algorithm receives an even number of messages. The forwarding only continues, when an uneven number of messages are received.

## 6.5 Improving the Contention-based Forwarding Algorithm

To remedy the identified phenomena, we introduce two modified CBF algorithms. Both maintain the core principle of CBF but add additional mechanisms that avoid starvation during the routing phase.

CBF with progress check and Duplicate Packet Detection (DPD), the algorithm is shown in Figure 6.12, applies an additional progress check rather than deterministically deleting a message on reception of its duplicate; if the received duplicate has *lower* progress than the ego-node, the ego-node recalculates the time-out and reschedules the contention timer. As the duplicate might have reached further than the original message, the timer recalculation allows a potential new node to broadcast first. To further reduce duplicates, the algorithm maintains a list of already processed message and flags whether it has observed a better option, i.e., a forwarder with more progress than itself. This means that the node will only participate in the process once. This overall process ensures progress and reduces duplicates, but at an increased delay, due to the timer recalculation, if no better forwarders are available. This approach is not well suited for highly mobile scenarios combined with long relevance durations of the information that is being forwarded, as the vehicle excludes itself from participating in the forwarding, even if it becomes the better option due to mobility. For short lived information, e.g., forwarding of information about a continuously updated congestion front where the information is updated at a high frequency, mobility would not have a significant impact, as updated information would be a new message.

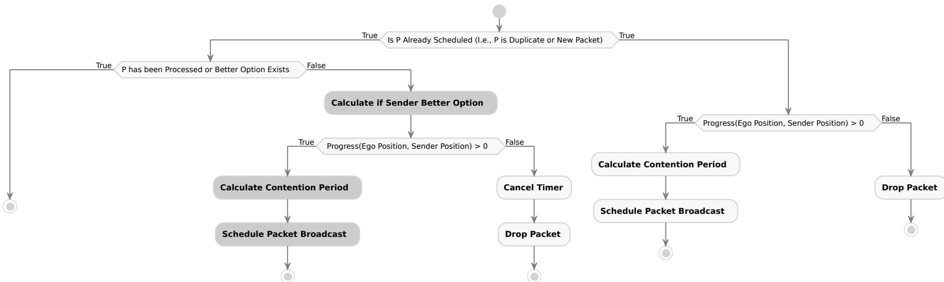


*Figure 6.12: CBF algorithm with progress check. The dark areas emphasize the modification.*

The second modified CBF algorithm is based on a randomized drop-out and duplicate packet detection approach, where each node only cancels its contention window with a given probability. This approach is illustrated in Figure 6.13. The reasoning is that by reducing the rate, the number of duplicates is increased, thus increasing the E2E reliability. The duplicate packet detection is introduced such that each node only participates in each session only once, i.e., reducing branching of messages to propagate through the network.

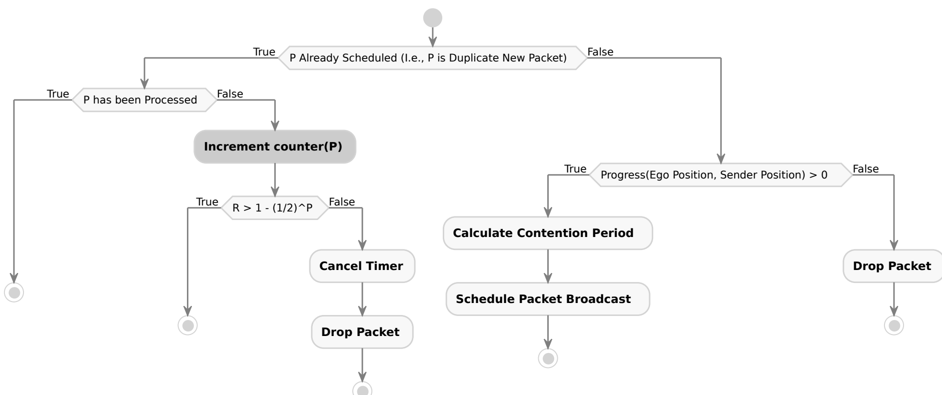


*Figure 6.13: CBF with randomized drop-out and DPD. In the evaluation the impact of the randomization with and without DPD is evaluated*

These modification focus on E2E reliability, but some use-cases exist, such as dissemination of "end of congestion"-notification, which do not necessarily benefit from the increased E2E delivery, as due to their continuously evolving nature, they require periodic update of the information. The modification is intended towards use-case that require E2E delivery, such as collection of PVD.

## 6.6 Broadcast Only Once – BCAST

The simple rebroadcast based approach described in this section is not defined by The European Telecommunications Standards Institute (ETSI), but is added for baseline comparison. It represents a reliable but rather inefficient approach for messages dissemination. It is inefficient as each node that receives a message rebroadcast it, resulting in a broadcast storm. To reduce the communication, the Identification (ID) of each received GeoNetworking message is recorded such that each message is only rebroadcasted once. Its dissemination scope can be limited through i.e., a maximum hop count, maximum Time To Live (TTL) or a geographic area, but otherwise every vehicle which receives the messages has to rebroadcast the message at most one time. The E2E delivery is high due to the large number of duplicated messages in the system, as this number corresponds to the number of vehicles, which is unnecessary during the geographic routing phase.

To make the approach comparable to the normative ETSI algorithms, we add the notion of *relevance area* which limits the propagation of a given message to the area between the source and the destination area. The implementation of this modification is of low complexity, but has a large impact on the communication overhead and if omitted the evaluation would depend more on the mobility scenario and number of nodes than anything else. To reduce the number of collisions, when multiple nodes rebroadcast a message at the same time, each forwarder waits $[t_0 : t_1]$ milliseconds before sending the message. The general approach is visualized in Figure 6.14; as long as the receiving nodes is within the relevance area, it rebroadcasts the message.

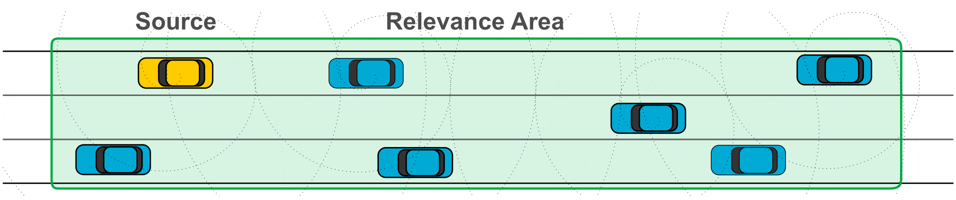


*Figure 6.14: In broadcast only once mode, each node acts as a forwarder as long as it is within the relevance area, rebroadcasting each received message exactly once. The relevance area is defined as the area between the source and the destination area, including it.*

## 6.7 Metrics, Evaluation Scenario and Simulation Setup

We use NS-3.19 to evaluate the behavior of geographic routing algorithms and to compare their performance under various conditions. The evaluation scenario consists of the road infrastructure described in Section 6.7.2, one source, located at the far end of the motorway, generates a message and sends it to a destination area at the other end of the road. Before defining the evaluation metrics, we introduce the following terminology:

- Geo-event – The generation of a geographically routed message.
- Duplicate – A duplicate is any message that is not the original message triggered by the geo-event.
- Forwarding event – Identified the forwarder sending the message to the MAC layer. Also identified by Tx event.
- Interfered – Defines a scenario in an environment with interference generated by Cooperative Awareness Messages (CAMs). Note that when discussing Greedy Forwarding, we also use the term 'with CAM communication' as Greedy Forwarding uses the content of the CAMs.
- Fading – Defines a scenario where the communication experiences frame error rates, which increase as a function of the distance between two communicating nodes.

### 6.7.1 Evaluation Metrics

We consider the following metrics for the evaluation:

- E2E delivery success rate is a measure of the ratio of message that are successfully routed from the source to the destination area, defined as that at least one vehicle in the destination area has received the message.
- Communication overhead is expressed by the following sub-metrics:
  - Total message count – The number of messages that were necessary to achieve E2E delivery.
  - Per message contribution – Measured as the average contribution per message in meters. This metric is specifically used for CBF and, while total message count is a more traditional metric in routing algorithms, the per message progress is more intuitive when discussing geographic routing algorithms, as it makes the results independent of the actual distance that was used.

- Progress probability – For geo-events that were not delivered at the destination are, we used the progress distribution to investigate how far the message travelled. This is interesting when using the algorithms for dissemination, i.e., where we want to maximize the number of informed vehicles.
- Unexpected behaviour – We present the distribution of send events over the routing area, and show that CBF behaves undesirably at certain locations.

### 6.7.2 Network Topology

The node topology used in the evaluation consists of vehicles that are semi-randomly distributed over a 2.5 kilometers, 6-lane, straight motorway. Figure 6.15 shows the mobility configuration.

For the evaluation we use a static mobility model, i.e., all vehicles remain at the positions at which they are initially assigned, throughout the entire simulation. This allows to evaluate the algorithms without the impact of mobility, thus focusing the evaluation on understanding the performance of the algorithms itself. The vehicle distribution is randomized in such a way that 1) there is always an E2E route, to avoid bias from scenarios which have no route, and 2) to make sure that vehicles do not line up exactly. The later is important for CBF, as vehicles which are exactly at the same distance from the destination area, would have precisely the same contention windows. Therefore, one vehicle is place at each lane with a predefined distance, $distance_{veh}$, and randomly distanced within $\pm\frac{distance_{veh}}{2}$, drawn from a uniform distribution. $distance_{veh}$ is determined by the vehicle density.

The source vehicle and the destination area are aligned such that they are populated evenly on both sides by vehicles to allow an equal level of interference for all forwarding operations. Therefore, the source vehicle is positioned at 500 meters and the destination area *starts* at 2000 meters, as shown in Figure 6.15. This leaves 1500 meters, through which the message has to be forwarded.

Table 6.2 summarizes the mobility parameters.

| Parameter: | Value: |
|---|---|
| Mobility type | Stationary |
| Number of lanes | 6 lanes |
| Lane width | 4 m |
| Vehicles per km | 60 – 300 veh/km |
| Inter-vehicle distance (per lane) | 20 – 100 m |
| Total number of vehicles | 150 – 750 |

*Table 6.2: Mobility Parameters*

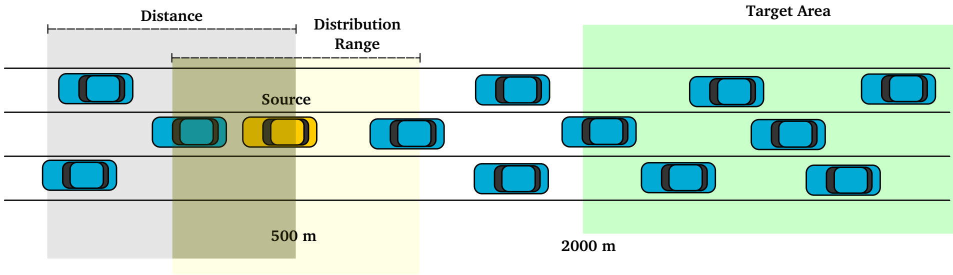


*Figure 6.15: A simplified illustration of the considered network topology. The mobility scenario consists of semi-uniformly distanced vehicles on a 2.5 kilometer long, where the source node and start of the destination area are located 500 meters into the topology.*

### 6.7.3 Network Scenario

For the physical layer configuration, we use a dual-slope log-distance path-loss model and evaluate the algorithms with and without fading by adding the Nakagami fading model. This allows us to evaluate how the algorithms react under high and low FSR at the edge of the communication range. We use the network topology described in Section 6.7.2 to create interference by making all nodes broadcast hello messages periodically. These hello messages are also used to populate the neighborhood information used for evaluating Greedy Forwarding.

The two models used are the ThreeLogDistancePropagationLossModel and the NakagamiPropagationLossModel. ThreeLogDistance is used to model path loss as a function of distance with a dual slope. As it can be seen in the propagation loss plot of the model in Figure 6.16, the limitation of a deterministic channel models is that it models the channel accordingly to a binary assumption; given a threshold, determined by the distance, the message is either always received or always lost, thereby ignoring the performance degradation at the edge of the of the communication range.

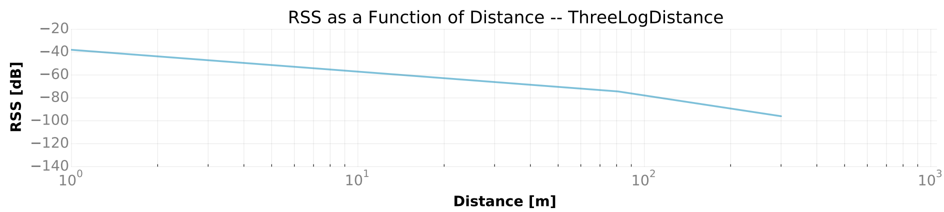


*Figure 6.16: Visualization of the NS-3 ThreeLogDistance model, using the define configuration.*

To extend the evaluation to also reflect that distance has an impact on the communication, the Nakagami propagation loss is applied in addition. Figure 6.17 shows how the

Nakagami propagation loss model, applied on top of the ThreeLogDistance becomes increasingly more stochastic as the distance between the sender and receiver increases.

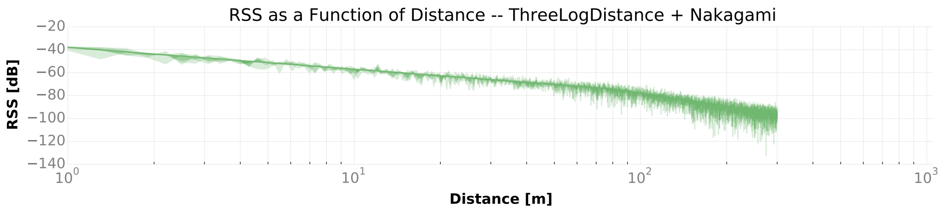


*Figure 6.17: Visualization of the NS-3 ThreeLogDistance + Nakagami models, using the define configuration.*

The resulting impact of the fading model on the FSR is shown in Figure 6.18.

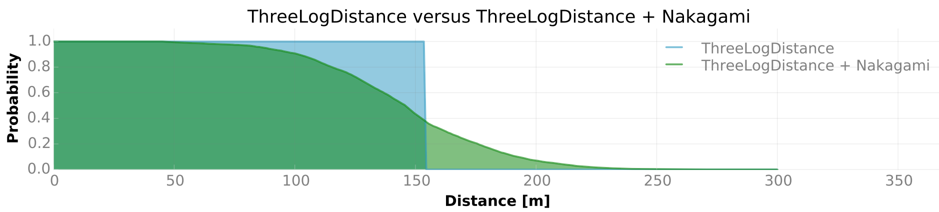


*Figure 6.18: Frame success ratio as a function of distance for ThreeLog and ThreeLog + Nakagami. ThreeLog alone has a hard cut off, where messages are either received or lost, while both combined provide a more realistic propagation loss degradation as a function of the distance.*

### 6.7.4 GeoNetworking Implementation

We have implemented the GeoNetworking layer logic, as it was defined in Section 6.4, in NS-3. That means that all the necessary logic for GBC is available with one exception. We have excluded the rate control mechanisms that is defined for removing nodes from the neighborhood information for two reasons: 1) the values for the parameters used are not given and 2) it is not defined how the mechanism is supposed to be used.

### 6.7.5 Discussion

This section discusses the consequences of the chosen simulation configuration and their impact.

**Static relative positions** – Except in cases with heavy congestion, static mobility does not realistically reflect the challenges that the algorithm can be expected to cope with. Static relative positions are however a necessity to remove the influence of topological changes and allowing to investigate what impacts the performance of the algorithms.

For the Greedy Forwarding evaluation, which depends on neighborhood information based on received messages from the surrounding vehicles, the impact of static mobility is negligible, if it is assumed that that the distribution of vehicles traveling in each direction is equal. Otherwise, when the vehicles are moving away from each others, the results are overestimating the performance, while the opposite is the case when they are traveling towards each other. The problem is, that the neighborhood information is updated for each received message throughout the entire simulation. This means that the neighborhood increases throughout the simulation, and that the results are underestimated for Greedy Forwarding. Therefore, we use the results for Greedy Forwarding to determine how the neighborhood information impacts the performance, rather than an direct evaluation of the Greedy Forwarding algorithm.

For CBF, the lack of mobility has minimal impact when we only consider a single geo-event and there exists a route between the source and the destination area, as the time-out is calculated on reception of the message.

**Fading** – The fading model, while improving realism compared to the non-fading model,has the disadvantage that it is too stochastic: As the numbers used to determine whether a message is delivered or not are drawn are independently, it is possible that if a specific message transmission is repeated, the results might be different, even though no other parameter than the random number has changed (mobility, interference, etc.). Translating this to a scenario with multiple vehicles in close vicinity, we can anticipate that the channel might be modeled more stochastic than in reality, depending on the distance between the sender and the receiver nodes. This is does not matter for the phenomenon we wish to observe but it does have an impact on the actual quantity. I.e., we may anticipate to observe side-effects to fading more often.

**Random Numbers** – To make the circumstance under which the simulations are executed comparable, we use four independent random number generators. I.e., one for the positioning of the vehicles, one for generating offsets between interference events (beaconing), one for the offsets of geo-events and finally one for the algorithms themselves, if a random number is used in the algorithm. This means that the only parameter changing over the same random number generator seed is how the algorithm reacts, while mobility and background communication stays constants. Additionally, to avoid bias from the network topology, we repeat each parameter combination 30 times.

## 6.8 Simulation Results

The following sections present and discuss the performance evaluation of the three algorithms w.r.t. E2E delivery success rate and communication overhead, as described in Section 6.7.1. BCAST is primarily used as a baseline scenario to show that a path from the source to the destination exists, Greedy Forwarding is evaluated w.r.t. to how large an impact the neighborhood information, or lack thereof, has. Finally, the different approaches for CBF are evaluated and compared to each other.

Please note that some figures show the confidence interval as a band rather than a bar. This is to avoid overlap between the bars and to ease readability.

### 6.8.1 BCAST – Re-Broadcast Only Once Evaluation

BCAST has a high, nearly perfect, E2E delivery success rate, as shown in Figure 6.19; the flooding based approach creates a high number of duplicates, resulting in a high probability of at least one forwarding event, making sure that the messages is delivered at the destination. Only at high densities, i.e., 300 vehicles per kilometer, a slight deviation can be seen, for the two scenarios with background CAM communication: This can be explained by interference and only in the case where the *initial* message is lost due to interference. When this occurs, the only copy of the message is lost and forwarding does not continue. As there is no mechanism for reliable E2E message delivery, all the evaluated algorithms suffer from this phenomenon.

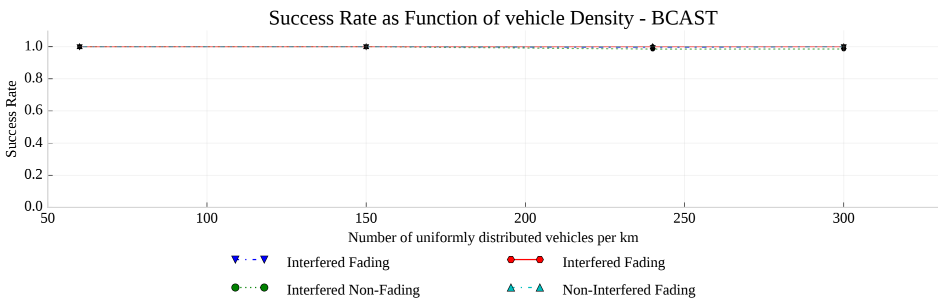


*Figure 6.19: Success Rate – BCAST*

BCAST's high E2E performance creates an, as expected, equally high overhead cost, as illustrated in Figure 6.20. Even though each single vehicle broadcasts each message only once, *all* vehicles rebroadcast it exactly once, thus, in the cases that the initial message has been successfully broadcasted, the total communication overhead is equal to the number of vehicles in the scenario. The deviation that can be seen in Figure 6.20 is pulled down due to messages that do not created duplicates due to the initial message being lost, as discussed above.

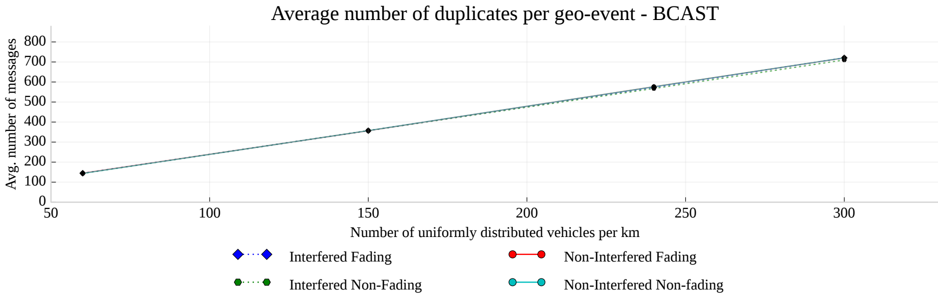


*Figure 6.20: Communication overhead – BCAST – The average number of duplicates per generated routing event. Including the original message.*

### 6.8.2 Greedy Forwarding Evaluation

E2E delivery success rate for the Greedy Forwarding algorithm as a function of vehicle density is shown in Figure 6.21, for four different conditions; each combination of with and without background CAM communication and with and without fading. The figure shows that Greedy Forwarding has a very low E2E delivery success rate for all but one of the combinations; without CAM, i.e., without background communication, and without fading.

To recap, Greedy Forwarding uses the neighborhood information to select the next forwarder. The neighborhood information is populated by all correctly received CAMs and PVDs message (routed messages). The lack of a mechanism for maintaining the neighborhood information can therefore result in a bias depending on message size and transmit frequency. For example using a one second warm-up duration, results in 10 transmit events while the unicast retransmission mechanism is limited to 7 retransmissions. As we use the same packet size in both directions, only the difference in transmission attempts has an impact.

We discus each of the four environments and how they impact the neighborhood information below:

- *Interfered, Fading:* Background CAM communication causes two challenges for successful E2E delivery; each CAM contributes to a successful population of the neighborhood information: as the simulation progresses, the neighborhood information includes more vehicles, increasing the inequality as discussed above. CAM communication also

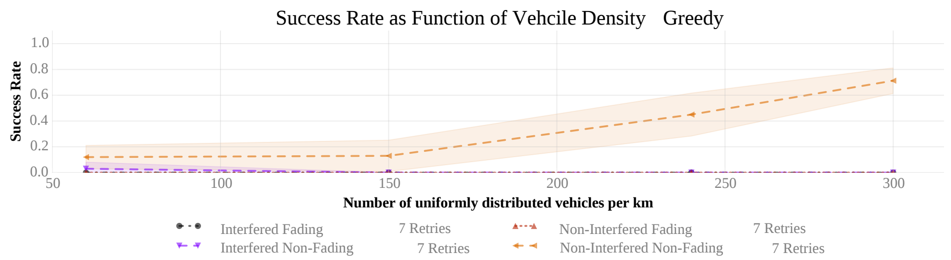


*Figure 6.21: E2E success rate – Greedy Forwarding generally provides low E2E success rate, except under specific circumstances.*

causes interference thereby further reducing the delivery probability. Greedy Forwarding is especially vulnerable towards interference, as the algorithm attempts to forward the message to the node furthest away, thus increasing the probability of hidden nodes. Fading combined with a limited number of retries, reduces the overall probability.

- *Interfered, Non-Fading:* E2E delivery is manly reduced by the neighborhood information and interference. The non-fading environment does increase the progress of each messages as illustrated in Figure 6.22, this is discussed further details later.
- *Non-Interfered, Fading:* The main limitation is caused by the unequal between the number of CAMs and number of retries of the PVD message; during the warm-up phase of the simulation, the vehicles broadcast 10 CAM messages while each geographically routed message has only seven tries. Thus the probability of receiving a message and updating the Location Table (LocT) is higher than a reply.
- *Non-Interfered, Non-Fading:* At low vehicle densities, the neighborhood information is over populated, reducing the E2E success rate. Interestingly, at high vehicle densities, the increased background CAM communication during the warm-up period causes the neighborhood information to shrink; due to the generally increased number of CAMs, there is an increase in interference, resulting in less message from the outer parts of the vehicles communication range. When the CAM communication is switched off, all vehicles in the neighborhood information are within the communication range and there is no interference which can cause message loss; thus the overall E2E performance increases.

Communication overhead in the context of Greedy Forwarding is marginal, and depends mainly on the MAC layer retries configuration. The per hop communication overhead is thus between one and the maximum number of tries. Due to the limited performance, the communication overhead is not calculated for the case of Greedy Forwarding. Rather we investigate the performance using the progress metric.

The progress of each routing event under all the evaluated conditions is visualized in Figure 6.22. It shows the drop-off rates as a function of distance, where messages that have been successfully delivered experience a drop at around 750 meters, i.e., the destination area. All drops before the destination area are therefore packet losses, indicating messages that did not manage to be delivered successfully.

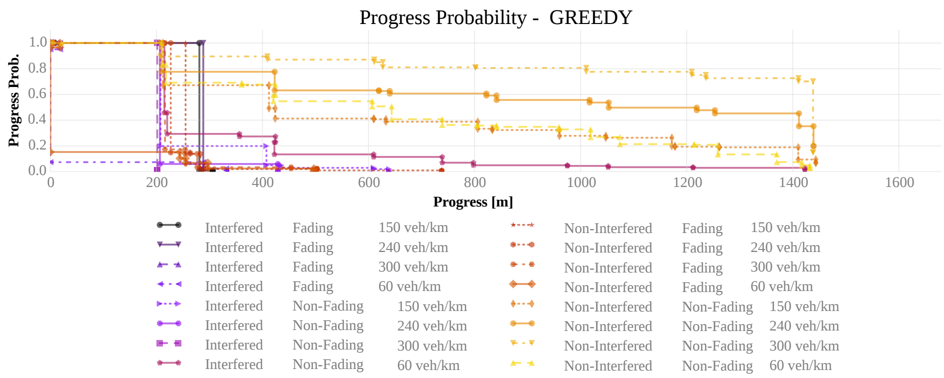


*Figure 6.22: Message progress – Greedy Forwarding – The average progress of geographically routed messages.*

In Section 6.8.1, it was mentioned that the primary reason for reduced performance was caused by the initial broadcast being interfered by e.g., a CAM broadcast; a similar phenomenon limits the E2E delivery performance in Greedy, as there is only one copy of each message. When this message is lost, the progress stagnates.

Figure 6.23 shows the progress of all scenarios *with CAM*, emphasizing the significant impact of interference; even at seven tries per message, there is a significant drop of probability: From approximately 50% without fading to a 90% drop off in a fading environment!

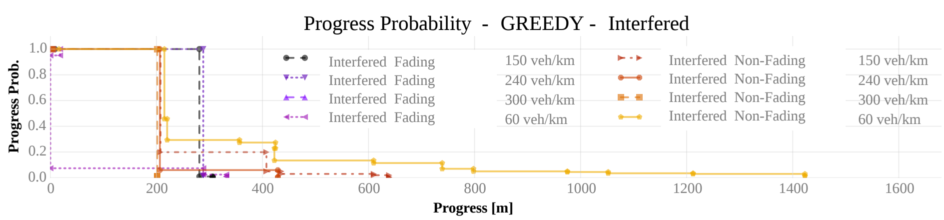


*Figure 6.23: Message progress – Greedy Forwarding – The average progress of geographically routed messages for all scenarios with CAM communication.*

### Summary and Potential Improvements of Greedy Forwarding

Greedy Forwarding is heavily dependent on the quality of the neighborhood information; how it is populated, what is recorded and, in particular how it is maintained when nodes are no longer considered neighbors. The quality has been shown to be very susceptible to both fading and interference. Under fading conditions due to the mismatch in the directional communication probability, and with interference due to the increased risk of hidden nodes when communication with nodes at the edge of the communication range.

A method for improving Greedy E2E performance would be to optimize the forwarder selection to make a balanced decision between the forwarder which provides the most forwarding progress and has a high, or at least reasonable, probability for receiving the message. However, this is expected to significantly increase the complexity of the implementation. Therefore, we continue with evaluating CBF and the different variants that were discussed earlier.

### 6.8.3 Contention-based Forwarding Evaluation

This section evaluates CBF and the derivatives. The goal is to improve E2E delivery, by making CBF more robust towards the uncertainties caused by the environment that the routing algorithms can experience. The evaluation metric consists of E2E performance as well as the costs associated with it; the number of duplicated messages each algorithm requires to deliver the message to the destination, if at all. The progress distribution and drop-off rate are used to explain what happens during the routing of the message. For the communication overhead, two metrics are used; the average number of duplicates generated per *successfully* delivered message and the per message contribution in meters. While the first is a typical metric used w.r.t. routing protocols, the second is more intuitive for geographic routing protocols that depend on duplicates, as this gives a more intuitive metrics when estimating the number of messages necessary for a geo-event under certain circumstances.

Table 6.3 provides an overview and a short description of the CBF variants.

### End-to-End Delivery

The E2E performance of the default CBF algorithm is illustrated in Figure 6.24, showing high delivery rate in environments with fading. In non-fading and low vehicle density scenarios, however, the E2E delivery rate is low, at only 40-50%, given that an E2E route *does* exist. Interestingly, and supporting the analysis, unreliable communication *improves* the E2E delivery, but, as discussed in the next section, at a high communication over-

| Algorithm | Definition | Description |
|---|---|---|
| Default CBF | CBF | ETSI defined CBF |
| CBF with DPD | CBF_DPD | Same as the ETSI defined CBF, but with an additional DPD such that each geographically routed messages is only used in broadcast mode/processed once |
| CBF with randomized drop-out | CBF_RND | Basically same procedure as the default CBF, but uses a randomized drop-out over the deterministic one. |
| CBF with randomized drop-out and DPD | CBF_RND_DPD | Besides randomized drop-out, this approach keeps track of already processed messages, thus reducing duplicate. |
| CBF with progress check and DPD | CBF_PROG_DPD | This approach introduces an additional progress check, before deciding whether to drop out of the contention window; the vehicle only drops out of the contention if it does not proved any progress, otherwise it resets and recalculates the time. When a better forwarder has been observed, it also set a flag for the specific sequence number, thus ignoring any future occurrences. |

*Table 6.3: Overview and definition of the different CBF variants. The main difference is how duplicate and contention drop outs are handled, while the time-out calculation is constant.*

| Parameter: | Value: |
|---|---|
| DIST_MAX | 1000 meters |
| TO_CBF_MIN | 2 milliseconds |
| TO_CBF_MAX | 100 milliseconds |

*Table 6.4: Configuration of CBF parameters.*

head. Overall, the E2E performance could be improved, especially for low vehicle density scenarios.

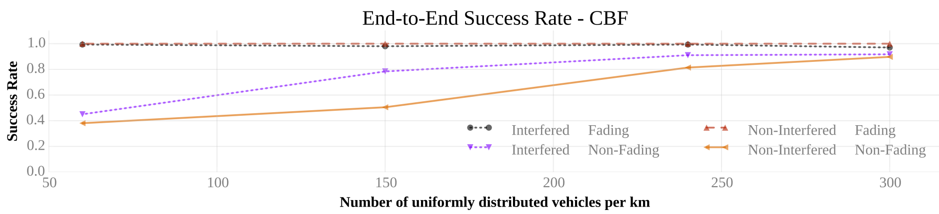


*Figure 6.24: E2E Success Rate – CBF*

Figure 6.25 and Figure 6.26 show the E2E performance for CBF DPD and CBF RND. These are selected to show the worst, represented by CBF DPD, and the best, CBF RND, E2E performances. The results for CBF DPD are used to illustrate that DPD is not the improving factor in the proposed CBF variants, but contributes to limiting the communication overhead. Figure 6.26 shows that randomizing decision whether to drop-out from the contention, improve the E2E performance, due to the relaxed assumptions.

The averaged E2E performance over all scenarios for all CBF variants are shown in Figure 6.27, showing that all of the evaluated CBF variants except CBF DPD provide a high E2E delivery performance. The improved performance is achieved as the alternatives are more robust towards both fading effects and interference. The difference is, as is investigated in the next section, mainly in the cost of the improved E2E performance in terms of redundant communication of duplicates.

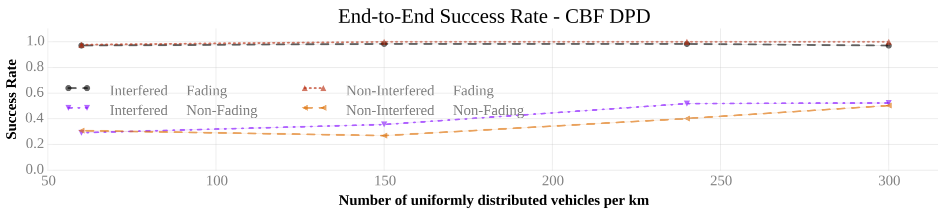


*Figure 6.25: Success Rate – CBF*

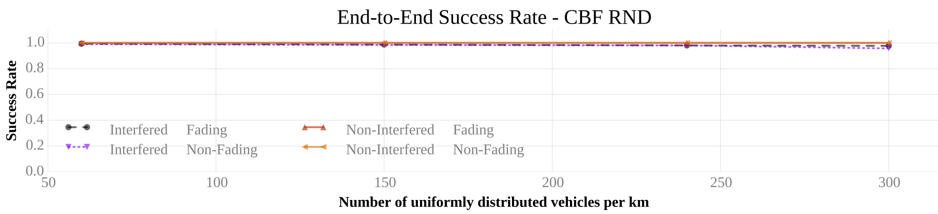


*Figure 6.26: End-to-End Success Rate – CBF with RND*

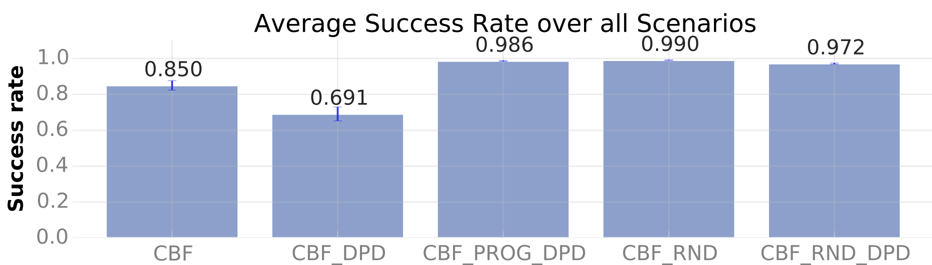


*Figure 6.27: Success rate averaged over all configurations, for each CBF variant.*

### Communication Overhead

In the considered scenarios, multiple factors impact the communication overhead. The distance between the source node and the destination area and the communication range of the nodes defines the minimum number of forwarding operations needed for a message to travel from the source to the destination. Fading has a larger but more error prone communication range, meaning that the minimum number of messages is different, and therefore not directly comparable with each other. Packet loss due to interference in the progress direction is another source of duplicates, where messages are transmitted but do not contribute to the progress. The scenarios without interference indicate the best case performance and are used as base line comparison while scenarios with interference indicate more realistic results. Before presenting the summarized communication overhead results, we use event diagrams to explain and discuss the properties of each algorithms and the causes for increased communication overhead.

Figure 6.28 and 6.29 show the event diagrams for CBF in a non-fading and fading environment, respectively. In non-fading, the is a high drop-off rate due to an even number of duplicates; all illustrated cases stop the routing due to two overlapping transmissions, most easily seen in the circled area (geo-event number seven). In a fading environment the E2E rate increases, but at a significant number of additional duplicates. This is usually caused by an uneven number of received messages, resulting in the wide fanning out of an individual geo-event. Figure 6.30 shows how introducing randomization alone increases the amount of transmission events, while adding duplicate detection, as illustrated in Figure 6.31, assures high E2E delivery and at the same times maintains the best property of CBF, low communication overhead. Finally, similar properties are maintained using progress checks, as shown in Figure 6.32.

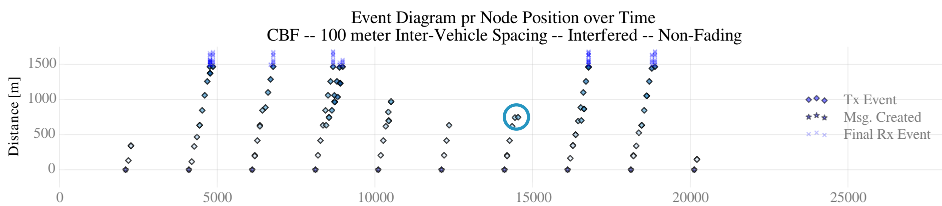


*Figure 6.28: Event diagram for 10 geo-events using the CBF algorithm under non-fading conditions. Geo-events are generated at distance 0 and the destination area begins at distance 1500.*

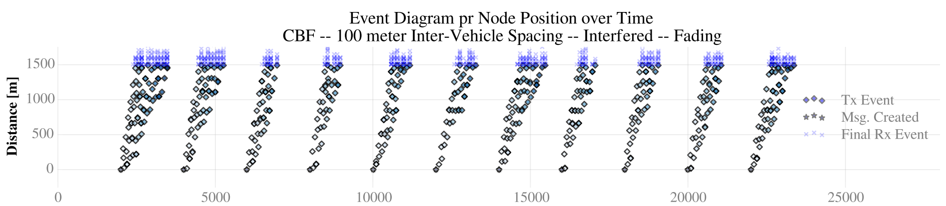


*Figure 6.29: Event diagram for 11 geo-events using the CBF algorithm under fading conditions. Geo-events are generated at distance 0 and the destination area begins at distance 1500.*

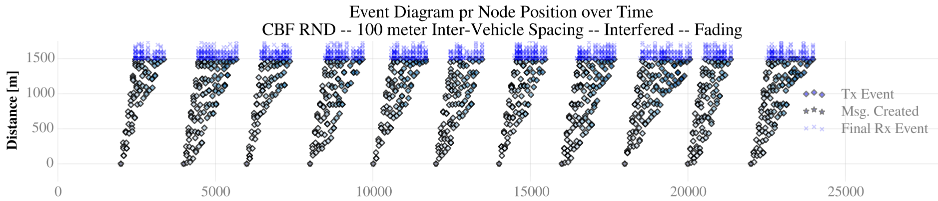


*Figure 6.30: Event diagram for 11 geo-events using the RND CBF algorithm under fading conditions. Geo-events are generated at distance 0 and the destination area begins at distance 1500.*

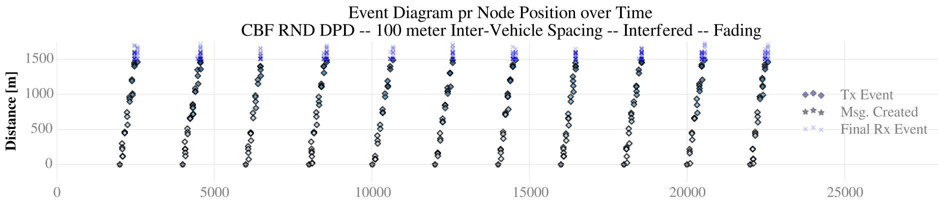


*Figure 6.31: Event diagram for 11 geo-events using the CBF RND DPD algorithm under non-fading conditions. Geo-events are generated at distance 0 and the destination area begins at distance 1500.*

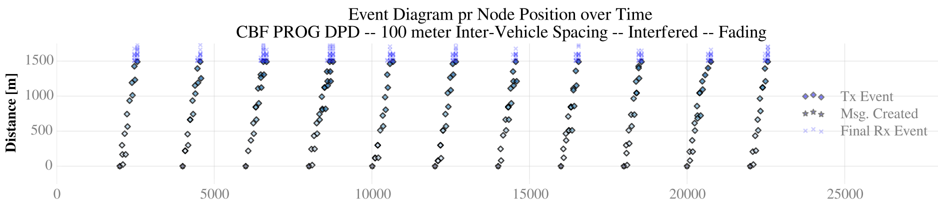


*Figure 6.32: Event diagram for 11 geo-events using the CBF PROG DPD algorithm under non-fading conditions. Geo-events are generated at distance 0 and the destination area begins at distance 1500.*

Figure 6.33 shows the average number of duplicates generated per successfully delivered geo-event. The figure shows that CBF DPD has the best overhead performance, with only 20.6 duplicates per successfully delivered message, while CBF RND needs almost 10 times the amount of messages.

### Per Message Contribution

geographic routing is about transporting information between two locations where, as mentioned in the previous section, a dominating factor is the distance between the two locations. To reflect the distance in the evaluation, we consider the per message contribution metric. It provides an estimator for determining communication overhead when

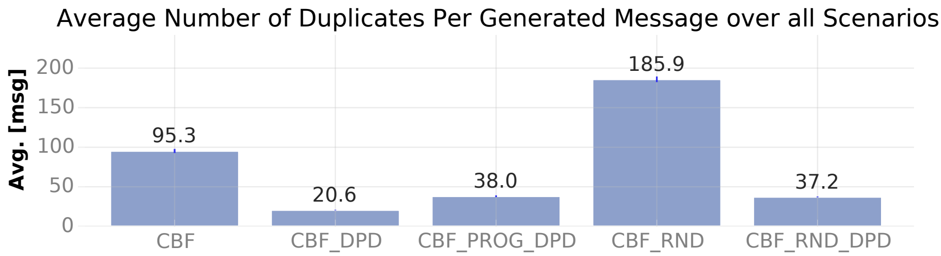


*Figure 6.33: Average duplicates per successfully delivered message, averaged over all configurations, for each CBF variant.*

generating a geo-event. Figure 6.34, 6.35 and 6.36 show the per message progress for selected CBF variants. Note that the scale is different, as we focus on the trend as well as the numerical value. The average per message progress is calculated as follows:

$$k = \frac{1}{n} \sum_{i=1}^{n} \frac{|p_{source}, p_{destination}|}{\sum m_i} \tag{6.3}$$

where k is meters per message, p is the geographic positions and $m$ are all messages sent during geo-event $i$. $n$ defines the number of successfully delivered geo-events, thus is a value between 0 and 330, corresponding to 30 repetitions, each generating 11 geo-events. The 95% confidence interval is represented by the shaded area.

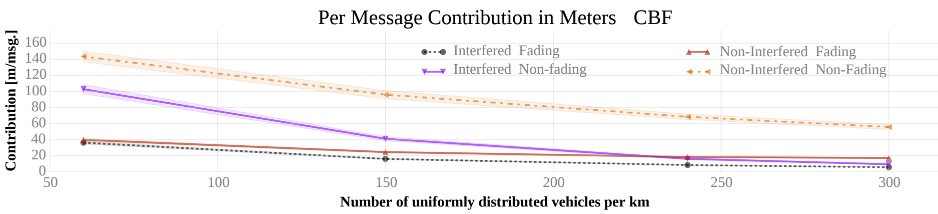


*Figure 6.34: Messages per Successfully delivered Message – CBF*

CBF in a non-fading and non-interfered environment provides the best per message progress, see Figure 6.34, as in these cases the algorithms finds the optimal forwarders. In the remaining three cases, the per message contribution drops to below 20 meters. In the case of CBF RND DPD, see Figure 6.36, it can be seen that the per message progress depends on the interference and the vehicle density. Interference due to lost messages and vehicle density due to an increased probability of vehicles in vicinity of each other, resulting in a similar contention time out.

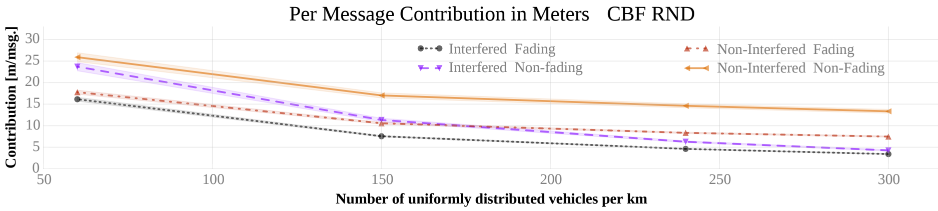


*Figure 6.35: Contribution – Average number of meters per message – CBF with RND*

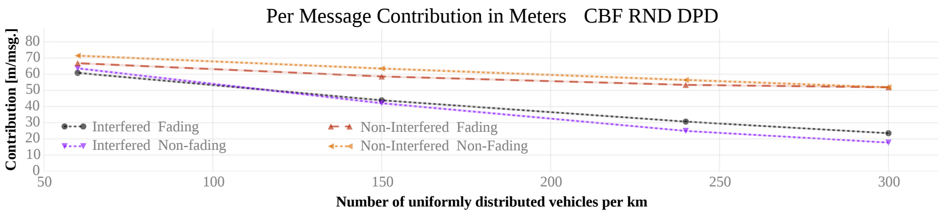


*Figure 6.36: Contribution – Average number of meters per message – CBF with RND and DPD*

Figure 6.37 shows the per message progress results averaged over all scenarios, for each of the evaluated CBF variants. It shows that all CBF variants with DPD provide high per message contribution, while the additional progress check in CBF PROG DPD provides best progress. CBF RND, while having a high E2E performance, has the lowest per message contribution due to the high amount of duplicates it generates.

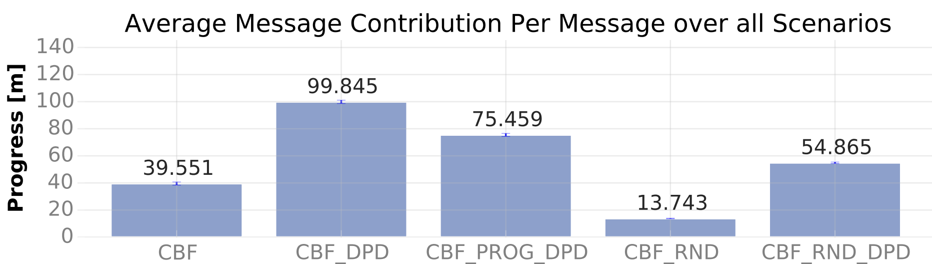


*Figure 6.37: Message progress averaged over all configurations, for each CBF variant.*

### Per Session Progress

Per session progress shows the measured drop off rate for the various CBF variants, as a function of the distance. Contrary to the previous results, it allows evaluating the performance of the CBF variants independent of whether the message is successfully delivered.

Figure 6.38, 6.39 and 6.40 show the progress distribution for the default CBF algorithm, CBF DPD and the remaining CBF variants, respectively. Variation around the destination area, i.e, at around the 1500 meter mark, results from the randomized vehicle position and the destination area.

CBF and CBF with DPD, Figure 6.38 and 6.39, suffer from message loss along the forwarding path, due to self cancellation, while all remaining CBF variants have a low drop off rate as the message progresses.

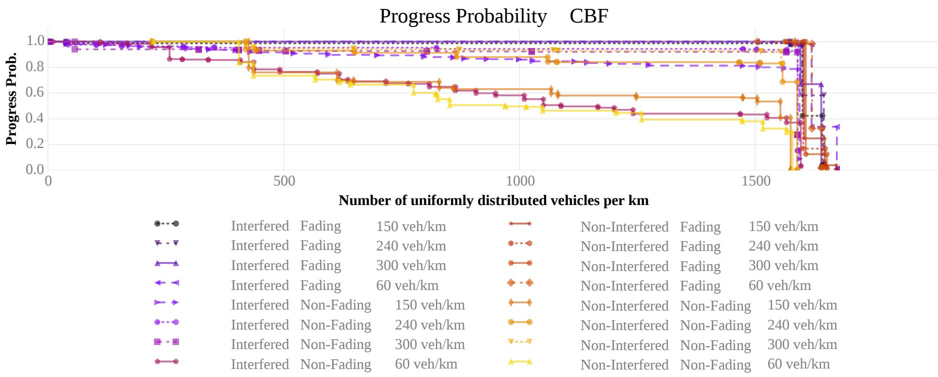


*Figure 6.38: Progress distribution – CBF. Lines that make it past 1500 meters are considered successfully delivered.*

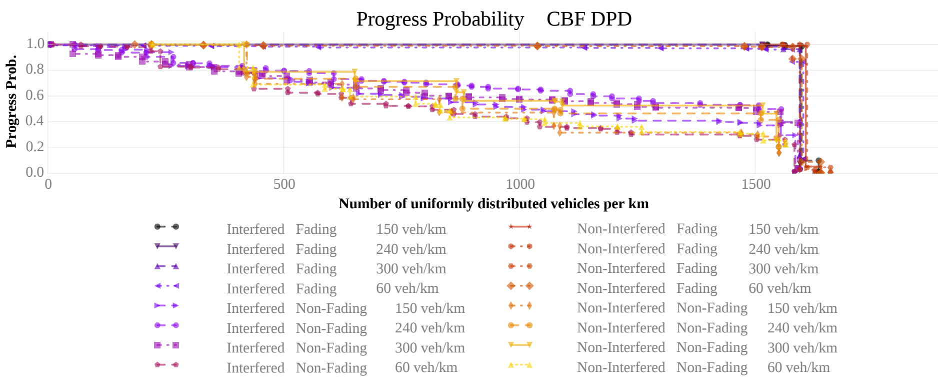


*Figure 6.39: Progress distribution – CBF DPD. Lines that make it past 1500 meters are considered successfully delivered.*

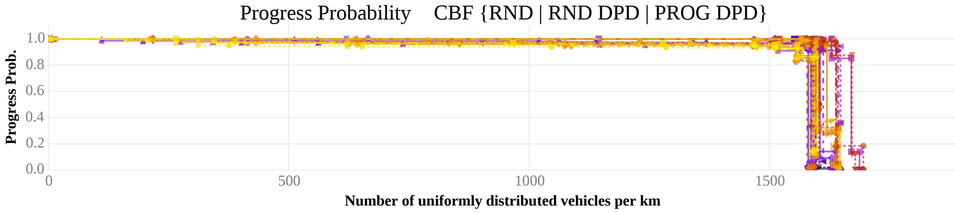


*Figure 6.40: Progress distribution for all remaining CBF variants. Lines that make it past 1500 meters (all) are considered successfully delivered.*

### Impact of Overshooting

Termination of a geo-event occurs either due to drop-out (message loss) during the routing process or when the message arrives (delivery success) at the destination area. However, if the message is consumed at the destination area and/or the defined destination area is smaller than the communication range, CBF can behave unexpectedly, as show in Figure 6.41 and Figure 6.42.

Both Figure 6.41 and Figure 6.42 show spikes in the number of send events just before the destination area, which begins at 1500 meters. Especially in the case of the two algorithms that do no track messages, i.e., without DPD, the number of send events are up to five time larger then otherwise observed. The increase of send events is caused by that the vehicle just outside of the destination area will always broadcast its message, as the forwarded message is consumed at the destination area and therefore these is nothing to cancel the contention time-out. Algorithms without DPD generate more send events in this area as there is a risk that the forwarding is restarted by a node far away from the destination area due to packet loss.

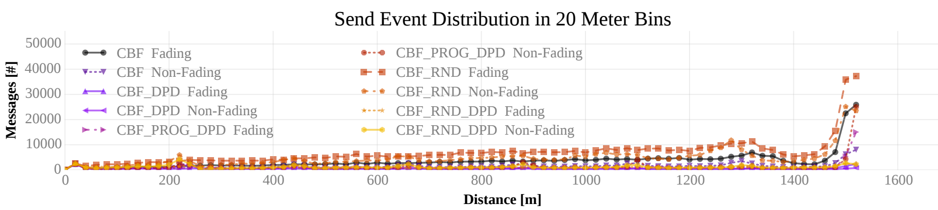


*Figure 6.41: Send event distribution over the routing area for each of the evaluated CBF variants.*

Figure 6.42 shows the impact of a scenario where the destination area is smaller than the communication range. For algorithms without DPD the impact is stronger than before as besides restarting the forwarding there is a risk of causing a ping-pong effect where vehicles on both sides compete to contribute to the forwarding, while the message has already been delivered at the destination area.

All CBF variants with DPD, reduce the communication overhead around the destination area significantly even when the destination area is smaller than the communication range. This is because vehicles ignore messages that have already been processed, as long as they fulfill the criteria of the algorithm.

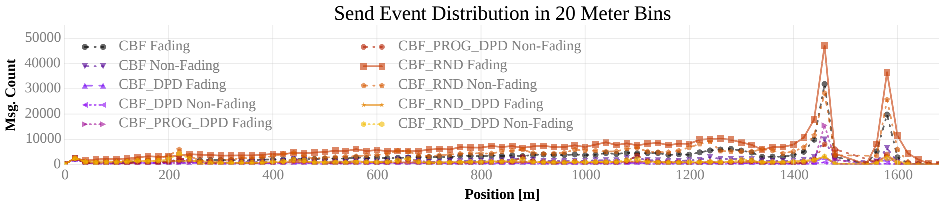


*Figure 6.42: Send event distribution over the routing area for each of the evaluated CBF variants when destination area is smaller than communication range.*

## 6.9 Conclusion

Geographic routing algorithms in the VANET environment must to be evaluated in the context of the use-cases for what they are used; here we consider PVD for continuously changing events that generate a stream of messages that each replaces the previous. Therefore the communication must be predictable and minimized while at the same time providing reliable E2E performance, especially in scenarios where the communication channel is shared with safety communication.

In this chapter we evaluated the default versions of Greedy Forwarding and CBF, both defined to be used in ITS-G5, through simulation. The evaluation shows that they, under certain circumstances, results in low delivery probability due to too optimistic assumptions on the reliability and timeliness of the communication. When the assumptions do not hold, both algorithms experience poor E2E performance and generate an uncontrollable amount of communication overhead. It was also shown that one of the algorithms, CBF, can be made reliable with only minor modifications, with near optimal and predictable communication overhead.

Greedy Forwarding was shown to be susceptible to the accuracy of the neighborhood information, primarily due to unbalanced communication probabilities; while the information that is used to update the neighborhood information is broadcasted at a high frequency, the probability of receiving at least one message in static scenario increases. The response has only a limited number of retries, thus reducing the probability of the response being delivered successfully if the number of retries is lower. This effect is made stronger by the main goal of Greedy Forwarding, which is to maximize the distance of each forwarding operation, as this effectively minimizes the probability of delivery in circumstances where the considered 'best' forwarder is located in a region with low reception probability.

CBF was shown to have multiple potential pitfalls, reducing the reliability and was shown to, surprisingly, have a higher probability of E2E delivery in environments with fading and high interference, but at the cost of significant communication overhead. Under optimal conditions, CBF does provide the minimal amount of overhead, but even under near to optimal circumstances, with low packet loss due to fading or interference that can cause delay, reduces the E2E delivery probability, e.g., MAC layer reordering of message transmissions, results in self cancellation.

Finally, relaxing the assumption on message sequencing and reliability of communication, by introducing a randomized decision making process bound by the received duplicate rather than limited by them was shown to make CBF significantly more robust in all evaluated communication scenarios, only limited by whether the initial message was successfully broadcasted. The introduction of DPD was shown to limit the amount of duplicates by removing branching, but also that DPD alone is not enough to improve the reliability.

## 6.10 Future Work

CBF with randomized drop-out and DPD performs well in the evaluated scenario. However, a significant challenge is to make it work, or evaluate how it works, under additional constraints like high mobility in combination with low vehicle density. Here the mobility of the vehicles breaks the assumption on which DPD is based on, as due to mobility the role as best forwarder, i.e., the one with the most progress, may change. This can be solved by modifying the DPD function to include randomization as well, and would potentially, at the cost of a predictable increase in messages, make the algorithm robust towards these scenarios as well.

The function for calculating the forwarding time-out in CBF can also be significantly improved to take contextual information into account. As discussed, the $DIST_{MAX}$ variable impact both the delay and the probability of collisions. By adding the neighborhood information that is already collected by the vehicles and combining it with a more realistic estimation of the actual communication range, each vehicle make educated guesses on whether it actually is the optimal forwarder, or, knowing that another vehicle has the same distance to the destination area, alter its own time-out, based on whether it knows is is a better option or not.

Coexistence with safety communication must also be further studied as it is essential that safety communication can still operate even though additional communication is introduced. Thus, the prioritization of safety message and the distribution of forwarded message in time has still to be investigated.

# Chapter 7

## Conclusion

In this work we have evaluated the challenges when collecting Probe Vehicle Data (PVD) generated by vehicles equipped with IEEE 802.11p based communication and processing devices in the context of a distributed infrastructure of Road-side Units (RSUs), i.e., access points that facilitate the information exchange between vehicles and application using the data. Key limitations identified and the proposed methodology to approach them are:

- **Enabling data communication when limited resources are available** – The upload of accumulations of large amounts of inter-dependent PVD can risk to require more resources than the single RSU can provide due to limited duration of the interaction or multiple vehicles competing for a limited resource. To enable the vehicle to successfully finalize its data upload, we define a method for temporarily pause and cache undelivered data until the next communication opportunity arises. The approach is evaluated using field trial measurements, showing that the incorrect detection of when communication between the RSU and the vehicle is possible presents a challlenge to this method. To accommodate with this challenge for large, coherent payload, a modified Media Access Control (MAC) contention mechanism is introduced. See Chapter 2 for details.
- **Limitations of application performance due to travel time** – Collection delay due to travel time was quantified as a function of the RSU distribution and traffic situation, and was shown to fluctuate in the average delay and spread of the delay. We evaluated how three algorithms, for estimation of the average speed, perform when the delay of PVD delivery is varied due to the traveled distance. The accuracy of using a predefined time window is limited by the travel distance as events are detected with a delay. Buffering of probe data can improve the accuracy but at a cost in the delay when the processed data is available to the application. Buffering of messages is suitable for collection of data for historical purposes while processing on reception has advantages when real-time data is needed. The selection of which method to use depends on the specific requirements of the application, however. See Chapter 3 for details.
- **Reducing resource requirements through management** – Motivated by the potentially large amount of information being generated by vehicles sampling all their sen-

sors everywhere at a high sampling rate combined with a limited amount of resources, in particular communication resources provided by a limited amount of RSUs, we defined a methodology that enables applications to specify exactly what they need and from where they need probe data, in the context of an distributed RSU infrastructure. Managing PVD results in a reduction of the amount of communication, storage and processing resources needed to facilitate the collection of the sensor data information. See Chapter 4 for details.

- **Reducing resource consumption through communication scheduling** – To facilitate a resource efficient method for information exchange between RSUs and On-Board Units (OBUs), we defined a method that uses contextual information about the communication properties of a specific RSU to schedule where the communication should be executed. The method consists of the generation of a so called performance map, which maps a communication performance metric (Frame Success Ratio (FSR)) with a geographic position, to identify the optimal geographic position for the vehicle to attempt to send data to the RSU. Using the same performance map together with the speed of the vehicles in the vicinity of the RSU, we can estimate the optimal broadcast frequency to use when disseminating information to vehicles, when using broadcast. The application of performance map is shown to reduce the amount of communication resources needed to realize the communication between RSUs and OBUs, by optimizing the delivery probability of individual transmissions. See Chapter 5 for details.
- **Extending communication range through multi-hop communication** – The duration between probe generation and probe processing, i.e., the delay before the information can be used by an application, is quantified using a simulation scenario and shown to vary both as a function of the geographic position where the probe is generated, the position of the RSU and the speed of the vehicle (which depends on the current traffic situation, driver attitude etc.). To avoid this delay for prioritized information collection or extending the communication range of RSUs, two geographical routing algorithms, that are expected to be used in ITS-G5, were evaluated and improved, resulting in an higher End-to-End delivery probability, when sending a messages from geographic position a to a geographic position b, while at the same time reducing the average communication overhead. See Chapter 6 for details.

The selection of which communication approaches to utilize depends mainly on the application that the data is being used for, and can by applied in various configurations, depending the application requirements. E.g., combining Controlled Probing with Disruption Tolerant Networking (DTN) for high resolution sampling and data collection or a combination of geographic forwarding and performance maps for high priority data collection of specific data. The achievable improvement by using the above defined methods is application specific, but each contributes to an improvement of the individual steps being part of the collection, either by specifying what to collected based on what is needed, as is the case of Controlled Probing, or improving the communication overhead during collection by using performance maps or reliable geographic forwarding.

# Chapter 8

## *Future Work*

In this work we have identified important general challenges and potential limitations when using a distributed infrastructure of Road-side Units (RSUs) for the collection of Probe Vehicle Data (PVD). For each of the identified challenges, we have proposed methodology that can limit the impact of the challenge or even circumvent it. However, a key element to identify the applicability of the defined methods is to evaluate the methods against specific applications and their requirements. A large part of this, however, requires a broader scope, going beyond periodic PVD and the considered technologies, with the purpose of matching application with the most suitable solution. With this in mind, we discuss the perspective of the individual chapters, and reflect over the future work:

**Chapter 2** – Use-case Study of 802.11p-based Infrastructure-to-Vehicle Communication: Heterogeneous communication environments can provide benefits by utilizing the best (most cost effective, cheapest, low delay) communication opportunity available depending on application requirements. Disruption Tolerant Networking (DTN) could conceptually be extended to cover multiple technologies, but at an increased delay due to a longer communication path (compared to store the data locally or on a nearby networking node.). Combining communication technologies and communication protocols would allow vehicles to use the approach for non-DTN communication as well.

**Chapter 3** – Properties of Probe Vehicle Data Collection: W.r.t. PVD data aggregation, we need to consider both how periodic PVD and other sensor data source, in particular traffic sensors and event PVD, can be used together to provide a high-level overview of the current traffic situation. Using, e.g., Controlled Probing, event information could be used to trigger the collection of additional information in specific area, thereby enabling the different information sources to support each other, rather than being considered self-contained entities.

**Chapter 4** – Controlled Probing – Concept and Design: A key functionality needed to fully realize Controlled Probing is the administration of how tasks are executed. While majority of traffic state monitoring applications require almost constantly updated information, a lot of special cases can benefit from management of what is collected. E.g., given a confidence interval needed and the type of information collected, a control algorithm should be defined that can autonomously determine when enough data has been collected, re-start collection tasks if the current level of information becomes stale or distribute tasks over time or to areas where resources are currently available.

**Chapter 5** – Reducing Communication Costs Through Performance Maps: DTN could benefit from performance maps in order to improve the segmentation of the data, such that only an appropriate amount of data is retrieved per RSU passing, and to be able to estimate how many RSUs are necessary until the information exchange is completed. Extending the approach with up-coming RSUs would also allow the vehicle to make informed decision based on context information on how to prioritize its communication; if the vehicle know it is close to a RSU it might postpone communication rather than apply geographic routing, or, if the opposite it the case, selected an alternative communication technology, which fulfills the current requirements.

**Chapter 6** – Extending Road-side Unit Coverage through Geographic Routing: The routing algorithm selection is heavenly influence by the application requirements. We have considered a scenario in which we expect data to be continuously update, or replaced. The vehicles should however have access to multiple routing algorithms, depending on whether the application requires dependability, timeliness or frequent information updates. To achieve this, the vehicles need mechanisms that allow them to make appropriate decisions, depending on the context, using all the available information; extended performance maps, as discussed above, including the road infrastructure and the heading of individual vehicles.

**Privacy Concerns** – An important topic that is not covered in this work is how to tackle the privacy concerns when collecting PVD. We have worked extensively with reducing the amount of PVD being generated and optimizing how the data that is generated is collected, primarily to improve the communication of the data from vehicles to the infrastructure. However, if drivers are not willing to contribute their data, these efforts might not be necessary.

The main privacy risk with the approach defined in this work it is that it in most cases generated long traces; assuming that vehicles generate probes between RSUs, it is simple to track drivers as they traverse though the road infrastructure. If the traces are buffered for long enough distances, the driver's home, work and spare time activities can also be identified, possibly leading to re-identification of which driver went where.

A key approach to improve the situation is to remove as much linkage between the driver and the probes the vehicle generates. This has to be solved on both the application and communication layers, as both can be used to de-anonymize the driver. From an application layer point of view, the probes must be generated such that the path of the vehicle cannot be recognized, and the approaches to solve the anonymity challenges are application dependent: For slowly evolving phenomena the time dimension can be increased thus making it harder to distinguish vehicles (easier to achieve $k$-anonymity[72] of where a specific vehicle is indistinguishable within $k$ other vehicles). From a communication layer perspective, using other vehicles as carries is a necessity to remove the link between vehicle generating probes and delivering them to the RSUs, thereby reducing the dimensionality of the data significantly: If a vehicle delivers its own probes while at the same time broadcasting safety messages, detailing the properties of the vehicles, the $k$-anonymity challenge becomes much harder, as RSUs have access to significantly more detailed information about the vehicle.

# Appendix A

## Acronyms

**AOI** Area of Interest

**OSI** Open Systems Interconnection

**BTP** Basic Transport Protocol

**CAM** Cooperative Awareness Message

**CBF** Contention-based Forwarding

**CRC** Cyclic Redundancy Check

**CCH** Control Channel

**DEN** Decentralized Environment Notification

**DENM** Decentralized Environment Notification Message

**DTN** Disruption Tolerant Networking

**DPD** Duplicate Packet Detection

**DSR** Dynamic Source Routing

**DYMO** Dynamic Mobile Ad-hoc Network (MANET) On Demand

**ETSI** The European Telecommunications Standards Institute

**E2E** End-to-End

**ECDF** Empirical Cumulative Distribution Function

**FCD** Floating Car Data

**FSR** Frame Success Ratio

**GPS** Global Positioning System

**GNSS** Global Navigation Satellite System

**GUC** GeoUnicast

**GAC** GeoAnycast

**GBC** GeoBroadcast

**HMM** Hidden Markov Model

**I2V** Infrastructure-to-Vehicle

**ID** Identification

**IP** Internet Protocol

**IPC** Industrial Personal Computer

**ITS** Intelligent Transportation System

**ITS-S** ITS-Station

**LOS** Line of Sight

**LocT** Location Table

**MAC** Media Access Control

**MANET** Mobile Ad-hoc Network

**MSE** Mean Square Error

**OBU** On-Board Unit

**PVD** Probe Vehicle Data

**PDRM** Probe Data Reporting Management

**RSSI** Received Signal Strength Indication

**RSU** Road-side Unit

**R-ITS-S** Roadside-ITS-Station

**VANET** Vehicular Ad-hoc Network

**V-ITS-S** Vehicular-ITS-Station

**UDP** User Datagram Protocol

**SAP** Service Access Point

**SCH** Service Channel

**SPAT** Signal Phase and Timing

**TCC** Traffic Control Center

**TCP** Transmission Control Protocol

**TTL** Time To Live

**UDP** User Datagram Protocol

**xFCD** eXtended Floating Car Data

**V-ITS-S** Vehicle-ITS-Station

**V2I** Vehicle-to-Infrastructure

**V2V** Vehicle-to-Vehicle

**V2V2I** Vehicle-to-Vehicle-to-Infrastructure

**VANET** Vehicular Ad-hoc Network

**PVD** Probe Vehicle Data

**QoS** Quality of Service

**WSA** WAVE Service Announcement

**WSM** WAVE Short Message

**WSMP** WAVE Short Message Protocol

**WAVE** Wireless Access in Wireless Environments

# Appendix B

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# Appendix C

# Simulation Configuration and Parameters for GeoNetworking Evaluation

## C.1 General Simulator Information and Configuration

| Parameter: | Value: |
|---|---|
| Simulation tool | NS-3 |
| Simulator version | 3.19 |

*Table C.1: Simulator Details*

| Parameter: | Value: |
|---|---|
| Warm-up | 2 s |
| Evaluation | 22 s |
| Total simulation duration | 24 s |
| Repetitions | 30 |

*Table C.2: General simulation parameters.*

| Parameter: | Value: |
|---|---|
| Mobility type | Stationary |
| Number of lanes | 6 lanes |
| Lane width | 4 m |
| Vehicles per km | 60 – 300 veh/km |
| Inter-vehicle distance (per lane) | 20 – 100 m |
| Total number of vehicles | 150 – 750 |

*Table C.3: Mobility Parameters*

## C.2 Communication Layer Configuration

[1] ThreeLogDistancePropagationLossModel

| Random Stream Type: | Usage: |
|---|---|
| Mobility (Uniform) | All mobility parameters are drawn from the stream, e.g., vehicle position. |
| Cooperative Awareness Message (CAM) (Uniform) | All CAM specific parameters, e.g., initial offset. |
| Geonet (Uniform) | Randomization of offset within inter-georouted message generation. |

*Table C.4: Random Stream Configuration and usage*

| Parameter: | Value: |
|---|---|
| **Physical Layer:** | |
| ccaThreshold | -85 dBm |
| edThreshold | -96 dBm |
| txGain | 0 |
| rxGain | 0 |
| txPowerStart | 10 |
| txPowerEnd | 10 |
| **Media Access Control (MAC) Layer** | |
| Number of tries: | 7 |
| **Application Layer** | |
| CAM message size: | 500 bytes |
| CAM frequency | 10 Hz |
| DENM message size: | 500 bytes |
| DENM frequency | 0.5 Hz |
| Total number of Decentralized Environment Notification Messages (DENMs) | 10 |

*Table C.5: Physical Layer Parameters*

| Parameter: | Value: |
|---|---|
| **Dual Slope**[1] | |
| Pathloss Exponent | 1.9 |
| Pathloss Exponent 2 | 3.8 |
| Pathloss Distance 2 | 80 m |
| **Nakagami** | |
| phy_m0 | 3 |
| phy_m1 | 1.5 |
| phy_m2 | 1 |
| phy_Distance1 | 50 |
| phy_Distance2 | 150 |

*Table C.6: Fading Configuration*